Engineering Challenges to the Long-Term Operation of the International Space Station

Committee on the Engineering Challenges to the Long-Term Operation of the International Space Station, Aeronautics and Space Engineering Board, National Research Council

ISBN: 0-309-51639-0, 54 pages, 8.5 x 11, (2000)

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Aeronautics and Space Engineering Board

Commission on Engineering and Technical Systems

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NATIONAL ACADEMY PRESS 2101 Constitution Avenue, N.W. Washington, D.C. 20418

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This study was supported by the National Aeronautics and Space Administration under contract No. NASW 4938. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

International Standard Book Number: 0-309-06938-6

Available in limited supply from: Aeronautics and Space Engineering Board, HA 292, 2101 Constitution Avenue, N.W., Washington, DC 20418. (202) 334-2855

Additional copies available for sale from: National Academy Press, 2101 Constitution Avenue, N.W. Box 285, Washington, DC 20055. 1-800-624-6242 or (202) 334-3313 (in the Washington Metropolitan area). http://www.nap.edu

Cover: Art by Marco Zambetti. Courtesy NASA, 1998.

Printed in the United States of America

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Preface

During the early 1960s, in the shadow of the Apollo lunar landing program, NASA undertook the study of three "next-step" scenarios for human operations and exploration in space. In the then-named Advanced Manned Mission Program, a lunar base was studied, flight opportunities to Mars and Venus through the 1980s were defined, and a conceptual design of an Earth orbiting space station was developed. Although the lunar base and the space station concepts could have been implemented using existing technology, national priorities dictated that these programs be deferred. Instead, the next major initiative in the development of flight systems for the human exploration of space was the development of a reusable launch system, the Space Shuttle.

In the mid-1980s, with the Space Shuttle operating and available for crew rotation and logistic support, the space station program was initiated. As the station design progressed through several interations between the mid-1980s and the early 1990s, it was progressively reduced in size and scope because of escalating cost projections. The international partners in the International Space Station (ISS) program include Japan, the European Space Agency, Canada, Italy, Russia, and Brazil. Russia's participation in full partnership with the United States includes the fabrication of ISS modules, the assembly of ISS elements on orbit, and, after assembly is completed (so-called "Assembly Complete"), day-to-day operation of the station.

The U.S. Congress has maintained an intense interest in the ISS program since its inception. In the Appropriations Act of October 27, 1997, the Senate included language directing the National Aeronautics and Space Administration (NASA) as follows (Public Law 105-65):

> . . . . [undertake] a study by the National Research Council . . . that evaluates in terms of the potential impact on the Space Station's assembly schedule, budget, and capabilities, the engineering challenges posed by extravehicular activity (EVA) requirements, United States and non-United States space launch requirements, the potential need to upgrade or replace equipment and components after Assembly Complete, and the requirement to decommission and disassemble the facility.

As the plans for this study were defined in detail, NASA and the National Research Council (NRC) decided the focus should be on the anticipated challenges in the continuous operation and maintenance of the ISS after assembly of the on-orbit facility has been completed. This would encompass the operational years, from late 2004 (if the current schedule holds) to 2020–2025. The final Statement of Task for this study is a negotiated departure from the original language of the enabling legislation in the Appropriations Act of October 27, 1997, eliminating an assessment of the assembly phase (i.e., the 46 component delivery and assembly flights during the five-year period for construction of the ISS on orbit). The final charter for this study is defined in the following Statement of Task:

> The study will assess the potential effect of long-term operational engineering issues on the budget and capabilities of the International Space Station (ISS) and, where appropriate, recommend procedures and hardware upgrades to mitigate their impact. The study will focus on the following issues:
>
> 1. Long-term ISS maintenance requirements.
> 2. Extravehicular activity (EVA) requirements to support ISS operations and maintenance (in light of experience with the Mir space station).
> 3. The use of an international fleet of launch vehicles to support the ISS.
> 4. The need for—and capability to—upgrade and replace ISS equipment and components after the station's assembly is complete. This includes the need to replace laboratory equipment as it becomes obsolete.
> 5. Decommissioning and disassembly of the station at the end of its useful life.

In March 1998, the NRC formed the Committee on the Engineering Challenges to the Long-Term Operation of the International Space Station, under the auspices of the Aeronautics and Space Engineering Board, to carry out this task (short biographies of the committee members appear in Appendix B). In September 1998, the committee met with NASA managers and congressional staff and was given presentations by NASA Space Station program managers on the plans for the development, assembly, and operation of the ISS. Two more meetings of the full committee were held at the NASA Johnson Space Center in Houston, Texas, in December 1998 and March 1999 to gather more detailed information. The full committee met again in May 1999 at the NASA Kennedy Space Center to review the draft report. In addition to these meetings of the full committee, committee members met with staff at NASA Headquarters, the Johnson Space Center, and the Goddard Space Flight Center, as well as managers at several NASA contractor sites, and conducted group assessments by telephone conference throughout the study.

This study focuses on the U.S. operation of the ISS after Assembly Complete, including cooperative efforts by the United States and Russia. The study and the ISS program have both benefited from lessons learned during the Phase 1 portion of the ISS program (March 1995 to June 1998), during which U.S. astronauts lived and worked on the Mir space station. A primary objective of the Phase 1 program was to develop an experience base in extended-duration space flight and space station operations for the United States. The committee, therefore, drew heavily on the experience of the U.S. astronauts who worked on Mir during the 33 months of the Phase 1 program, and the committee's recommendations regarding the ISS crew are, therefore, based largely on this unique experience base. The work of the committee was enhanced in this regard by having one Phase 1 Mir astronaut as a committee member and another who shared his experiences with the full committee in a briefing at the NASA Johnson Space Center. The committee's recommendations pertaining to crew matters were developed through a variety of sources including: personal accounts of U.S. astronauts; NASA's documentation of the Phase 1 Mir experience; interviews of the Mir astronauts conducted as a part of the "Living History" initiative in progress at the NASA Johnson Space Center; and NASA's responses to questions from committee members pertaining to the Phase 1 Mir experience (included in this report as Appendix C).

The Governing Board Executive Committee of the National Academies that approved the plan for this study in November 1997 expressed a special interest in NASA's plan for ensuring access to the ISS. The board requested that the committee's assessment of the national and international launch vehicle fleet specifically address the ability of the fleet to sustain the ISS throughout its operational lifetime. That question was pursued with NASA and is addressed in this report.

The committee would like to thank the many dedicated individuals at NASA and their contractors who took the time to answer the committee's questions pertaining to the ISS. The committee would particularly like to thank Mr. Pat McCracken, NASA Headquarters, and Mr. Bruce Luna, NASA Johnson Space Center, for acting as liaisons between NASA and the committee throughout the study.

This report is the committee's response to the Statement of Task. The report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the NRC. The purpose of this independent review was to provide candid and critical comments to assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Aaron Cohen, Texas A&M University
George J. Gleghorn, TRW Space and Technology Group (retired)
Richard Kohrs, Kistler Aerospace Corporation
Walter B. LaBerge, Institute for Advanced Technology (retired)
Louis J. Lanzerotti, Bell Laboratories, Lucent Technologies
Simon Ostrach, Case Western Reserve University
Cornelius J. Pings, Association of American Universities (president emeritus)
Norman E. Thagard, Florida State University
John M. Logsdon III, Space Policy Institute

While the individuals listed above provided constructive comments and suggestions, responsibility for the final content of the report rests entirely with the authoring committee and the National Research Council.

Thomas Kelly, *chair*
Committee on the Engineering Challenges to the Long-Term Operation of the International Space Station

Contents

Executive Summary

The International Space Station (ISS) is truly an international undertaking. The project is being led by the United States, with the participation of Japan, the European Space Agency, Canada, Italy, Russia, and Brazil (see Figure ES-1). Russia is participating in full partnership with the United States in the fabrication of ISS modules, the assembly of ISS elements on orbit, and, after assembly has been completed (so-called "Assembly Complete"), the day-to-day operation of the station. Construction of the ISS began with the launch of the Russian Zarya module in November 1998 followed by the launch of the U.S. Unity module in December 1998. The two modules were mated and interconnected by the crew of the Space Shuttle during the December flight, and the first assembled element of the ISS was in place. Construction will continue with the delivery of components and assembly on orbit through a series of 46 planned flights. During the study period, the Assembly Complete milestone was scheduled for November 2004 with the final ISS construction flight delivering the U.S. Habitation Module.

This study of the engineering challenges posed by long-term operation of the ISS shows that the National Aeronautics and Space Administration (NASA) and the ISS developers have focused almost totally on completing the design and development of the station and completing its assembly in orbit. After ISS Assembly Complete, the primary work on orbit will shift to scientific and engineering research, ISS operations, and the maintenance of ISS systems and experiments. Therefore, many of the issues and opportunities related to long-term operations have not yet been addressed thoroughly by NASA except as they apply to the more immediate tasks of ISS assembly.

Despite this near-term focus, the committee found no major engineering problems with the design of the ISS that would adversely affect long-term operations. Most of the deficiencies can be corrected with procedural changes and equipment or software upgrades in time for incorporation at ISS Assembly Complete. Although funding for most of these changes has not been committed because of the higher priority of current program issues, funds are likely to be available in the out years of the program as ISS assembly proceeds toward completion.

In the first committee meeting in September 1998, the committee reviewed the report of the Cost Assessment and Validation (CAV) Task Force of the NASA Advisory Council, which had been released several months earlier (CAV, 1998). The Terms of Reference for the CAV Task Force were compiled by NASA on October 14, 1997, concurrent with, and in direct response to, the congressional interest expressed in the Appropriations Act of October 17, 1997, which also chartered this study. The CAV report was published in April 1998, just one month after the official start date of this study. The report examined in detail the cost and schedule risks in the ISS program, focusing on the assembly phase of the program and predicting a one to three year slip in schedule and a most likely date for Assembly Complete of December 2005.

The committee found the CAV report to be a comprehensive and timely study of the ISS budget risks and decided that it need not be duplicated and that the study on the long term operation of the ISS should be complementary to it. Therefore, the committee decided to focus on the engineering challenges of long-term ISS operations and delve into budget issues only if they were not covered in the CAV report. However, the CAV report covered the budget issues thoroughly and the recommendations in this report fit the CAV's budget assumptions for the operational phase.

The committee made 36 recommendations, 17 of which are highlighted in this Executive Summary. All of the committee's recommendations are treated in detail in the body of the report.

In the area of communications and data handling, the committee concluded that increases in communications uplink and downlink bandwidths, and an increase in the availability of communications links through the tracking and data relay satellite system (i.e., increased antennae mutual visibility time) will be critical to the efficiency of long-term operation of the ISS. Enhanced communications will be an enabling innovation for long-term ISS missions by allowing time for on-orbit training and for the introduction of interactive maintenance and repair tutorials that will facilitate making detailed equipment diagnoses and evaluations and will support direct interaction between the crew and the principal investigators (PIs) of the experiments. Thus, operating efficiency would be increased and the aggregate demands on crew time for long-term operations would be eased. These changes should be reflected in NASA's plans for the ISS. This subject is discussed further in Chapter 5.

Recommendation. The National Aeronautics and Space Administration should make increasing the uplink bandwidth a high priority and should evaluate the importance of video communications.

Recommendation. The International Space Station antennae should be relocated in a configuration that allows continuous communication through the tracking and data relay satellite system.

NASA's control procedures for space flight operations have evolved over many years of diligent attention to detail, and they are excellent. These procedures are highly refined and have been highly successful since the very first suborbital Mercury flight some four decades ago. The challenges associated with the long-term operation of the ISS, however, will be very different from the challenges of the short-term human space flights of the past 40 years.

The committee was concerned that the ISS operations and maintenance workload might leave ISS flight crews little time for research as happened in recent years on the Russian space station, Mir. NASA has not done sufficient analyses to alleviate this concern. The committee concluded that a rigorous analysis will be necessary to determine if the crews of the ISS will have enough time to conduct research. To that end, NASA should prepare a long-term "design reference mission" showing projected clusters of crew activities against a timeline. It would be useful, for example, to show a typical 30-day timeline with the Space Shuttle docked either at the beginning or the end of the 30-day period. This would help determine if measures to increase onboard crew efficiency and conserve the crew's working time will be necessary. This subject is discussed further in Chapter 3.

Recommendation. The National Aeronautics and Space Administration should reassess the crew's activities against a more realistic timeline based on the Phase 1 Mir experience, as well as experience gained during assembly of the International Space Station. If the crew could take on more of the day-to-day mission operations, the aggregate requirements for ground crew personnel would be reduced.

The time on orbit of three to four months for an ISS crew suggests a mode of operation different from the operational mode appropriate, for example, for the much shorter duration Space Shuttle flights. This difference was noted by several of the U.S. astronauts who lived and worked on Mir in the Phase 1 program and who had had prior flight experience on several Space Shuttle flights. The observation is also included in the "Phase 1 Lessons Learned" documentation of August 26, 1998 (NASA, 1998a). The flight crews who will have months of accumulated experience with the equipment and experiments on board the ISS, will be extremely well qualified to participate in the planning of maintenance tasks and to implement changes to experiment protocols deemed necessary by the principal investigators (PIs). The resourcefulness of flight crews is legendary in NASA's history of space flight operations, and they should be delegated the responsibility for a great deal of the day-to-day planning of on-orbit operations. NASA should reassess its basic philosophy of space flight operations to take advantage of their expertise. This subject is discussed further in Chapter 3.

Recommendation. The National Aeronautics and Space Administration should allow the International Space Station (ISS) crew on orbit to contribute to the development and optimization of the daily timeline. The time saved would allow the crew to devote more time to scientific research. Oversight of the accomplishment of crew tasks aboard the ISS should be maintained by mission control through periodic flight crew/ground controller progress reviews.

Recommendation. The National Aeronautics and Space Administration should adopt the practice demonstrated during the Mir program of direct communications between the crew and principal investigators (PIs). Crew members and PIs should be able to exchange data and instructions to enable the crew to carry out experiments in the way that best fulfills the goals of the experiment. Computer links should be developed and communications systems upgraded to provide real-time assessments of the data and the capability of responding to change.

Recommendation. The National Aeronautics and Space Administration (NASA) should develop a new concept of operations for the long-term operation of the International Space Station that includes the integration of new information technologies into mission control center processes. NASA should consider adopting the Russian operational practice used for Mir (i.e., maintaining a small team in the mission control center and relying on experts on call with remote access to the data and personnel in the mission control center).

Recommendation. The National Aeronautics and Space Administration should reassess its crew requirements for the International Space Station and consider including a payload specialist in the seven-person crew.

All of the information provided to the committee shows that the baseline extravehicular mobility unit (EMU) is a mature system that can be expected to support the ISS operational phase. Nevertheless, many improvements could be made, including reducing prebreathing requirements, increasing the use of robotics for extravehicular activities (EVAs), and using more autonomous robotics that demand less crew time, skills, and training. Long-term operations will also afford a unique opportunity to use the ISS as a test bed for advances in EVA equipment and technology. This subject is discussed further in Chapter 4.

Recommendation. The National Aeronautics and Space Administration and its international partners should develop a plan to incorporate improved control modes for the baseline robotic systems on the International Space Station (i.e., the space station remote manipulator system and the special purpose dexterous manipulator) that would simplify their operation and reduce astronaut training time (e.g., "flying the end point"). The plan should address cost and safety considerations as well as teleoperation by ground-based operators.

Recommendation. The National Aeronautics and Space Administration should assess the potential improvements in extravehicular activities from the introduction of new robotic technology into human-robot systems. This assessment should include a comparison of the cost for development and implementation and the potential cost savings and risk reduction associated with the use of these systems.

Recommendation. The National Aeronautics and Space Administration should use the International Space Station (ISS) as a technology test bed for advanced extravehicular activity (EVA) systems, including robotic systems to support long-term ISS operations and future space missions. Rather than introducing only incremental changes, revolutionary approaches should be pursued to developing new materials, achieving greater mobility, and incorporating new technologies for both EVA suits and robotics systems in support of future exploration initiatives.

The committee found that the requirements for logistics and resupply flights and for on-orbit maintenance could be refined and probably reduced by applying more practical, targeted failure analysis and logistics management techniques based on current NASA and Air Force space operations experience. The techniques NASA is currently using for failure prediction and logistics management are outdated. Overcompensating for the general nonspecific nature of the analyses will lead to excessively large and costly inventories of spare parts, maintenance depots, and ISS resupply flights (Butina, 1998; NASA, 1998b). With better planning, the ISS program could decrease logistics and maintenance costs and reduce the number of resupply flights required, thereby reducing the frequency of disturbances to the ISS microgravity environment for critical experiments. This subject is discussed further in Chapter 3.

Recommendation. The National Aeronautics and Space Administration should greatly expand its focus on failure detection, isolation, and recovery (FDIR) in conjunction with the failure modes and effects analysis (FMEA). The following issues should be addressed specifically:

- allocation of responsibility to automated/nonautomated functions
- consistency of the FDIR with known failures
- integration with space and ground crew training and logistics

Several models exist for logistics planning. NASA has developed a computerized provision planning system for the EMU that tracks current inventory and projects future requirements based on a number of program parameters. This system could be used as a model for improving logistics planning. Lessons learned from the Hubble Space Telescope Program could also be used to improve planning. This subject is discussed further in Chapter 3.

Recommendation. The National Aeronautics and Space Administration should reassess its current philosophy for providing spare parts, as well as the depots and associated personnel required to maintain them for the operational International Space Station (ISS). The criticality of hardware, wear-out factors, and the potential for subsystem upgrades should be considered in the reassessment. The logistics, reliability, and mission assurance personnel for the ISS should establish an ongoing liaison with their counterparts in the Hubble Space Telescope program to evaluate a new philosophy for the ISS and the possibility of reducing associated costs.

ISS management has expressed serious concerns about the ability of the Russian partners to deliver on their commitments. Nevertheless, NASA's options for reducing the dependency of the ISS Program on Russia are limited. NASA described three options:

- Option 1. Provide funding to Russia as necessary to complete and sustain all Russian contributions.
- Option 2. Provide funding to Russia for items necessary to continue the ISS Program in the near term while funding the U.S. capabilities (e.g., U.S. propulsion module) necessary to eliminate dependence on Russian participation, thereby establishing U.S. autonomy, in the long term.
- Option 3. Provide no funding support to Russia and adjust the schedule of the ISS Program, as necessary, to accommodate late Russian deliveries.

The committee believes that a more thorough analysis of these options is required, particularly as they apply to the long-term operation of the ISS after Assembly Complete. This subject is discussed further in Chapter 2.

Recommendation. The National Aeronautics and Space Administration should develop a concise comparison of Options 1 and 2 to document the relative costs, as well as the program risks and benefits, associated with implementing Option 2 in order to reduce International Space Station (ISS) dependence on Russia and achieve autonomy for the ISS Program in the long term. The cost estimates should include the following items:

- the incremental cost of operating the Space Shuttle to replace Soyuz/Progress logistics flights
- the cost of developing a U.S. propulsion module and delivering it to the ISS
- the cost and risk associated with integrating a U.S. propulsion module with the ISS this late in the ISS program
- other costs that may accrue in establishing U.S. autonomy
- risks to the program schedule

The committee reviewed NASA's plans for using the international launch vehicle fleet to ensure access to the ISS assuming that over the long-term operation of the ISS one or both of the primary launch vehicles supporting the ISS (i.e., the Space Shuttle and the Soyuz) would be in a stand-down. NASA has not yet seriously considered this aspect of contingency planning for operations in support of the ISS after Assembly Complete. NASA has been operating on the assumption that either the Space Shuttle or the Soyuz, or both, will be available for crew launches.

If both the Space Shuttle and the Soyuz were concurrently in a stand-down mode, however, support of ISS crew operations would no longer be possible. Other vehicles, particularly the autonomous transfer vehicle (ATV) (propellant logistics) launched by Ariane and the Japanese H-II transfer vehicle (HTV) launched by the H-II launch vehicle, are part of the ISS logistics support baseline and could be used for noncrew-related logistics operations in case of a concurrent stand-down of the two primary vehicles. In one scenario, the ISS would be moved to a higher altitude to prolong its life and reduce logistics flight requirements. The ISS can survive without a crew, and, like the Soyuz/Progress logistics resupply vehicle, the ATV can dock without a crew. In this scenario, the contingency plan for the concurrent stand-down mode, therefore, is to "mothball" the ISS by moving it to a higher orbit and replenishing propellant via the ATV in an automatic docking mode.

The committee believes that NASA should look more carefully at its contingency plans for the operational phase of the ISS and assess other options for ensuring its survivability in case of a concurrent stand-down of the Space Shuttle and the Soyuz launch vehicles, and the Soyuz/Progress logistics resupply vehicle. This subject is discussed further in Chapter 2.

Recommendation. The National Aeronautics and Space Administration (NASA) should develop contingency planning for personnel transport and resupply during the operational phase of the International Space Station (ISS). The assessment should identify viable options other than moving the ISS into a high storage orbit in case of a concurrent stand-down of the Space Shuttle, the Soyuz, and the Soyuz/Progress vehicles. NASA's plan should accommodate new launch vehicles that may become operational during the operational lifetime of the ISS for both crew transport and ISS resupply. The plan should address the relative costs of the various options for ensuring access to the ISS.

NASA plans to deorbit the ISS with a controlled reentry at the end of its useful operating lifetime on orbit. The committee believes that NASA should conduct a rigorous reassessment of entry probability criteria and the risks associated with ISS reentry to determine if the present decommissioning/deorbiting plan should be changed. NASA's plan should be consistent with the agency's objectives of maximizing the safety of the operation and minimizing the potential risks associated with the reentry of such a large object. This subject is discussed further in Chapter 6.

Recommendation. Because of the potential hazards associated with the reentry of relatively large objects, the safety requirement for International Space Station reentry should be more stringent than the requirement for other National Aeronautics and Space Administration operations (i.e., the chance of casualties should be much less than 1 in 10,000).

Recommendation. The National Aeronautics and Space Administration should undertake a thorough analysis of International Space Station reentry operations, including ranges of uncertainty associated with the multiple variables of reentry operations. The analysis could take the form of a Monte Carlo simulation of reentry operations and projected impact areas to characterize the hypothetical potential for property damage or casualties. The analysis should include the sequence of operations, possible failures, and consequences of failures, from the initiation of reentry operations to final impact. Uncertainty variables should include, but should not be limited to, reliability characteristics, duration of burn, atmospheric density, ballistic coefficients of fragments, population densities, and the characterization of acceptable impact areas.

Finally, NASA has an important ongoing program to identify preplanned product improvements (P^3I) for the ISS. Under this program, the staff of the ISS Program Office, and the appropriate offices in the Engineering Directorate at the NASA Johnson Space Center, recommend candidate items for ISS system or component upgrades. Some of these upgrades could significantly reduce maintenance and resupply requirements for the long-term operation of the ISS thereby increasing crew efficiency. Although the P^3I program is being conducted carefully and responsibly, its current funding is grossly inadequate. NASA should assign high priorities to the preplanned product improvements, and other specific items that will contribute to the efficient operation of the ISS after Assembly Complete and make the ISS less dependent on Russian supplied hardware. NASA should prepare a long-range budget plan for P^3I to ensure that cost-effective and operations-effective upgrades are developed in time for ISS Assembly Complete. To ensure that NASA does not defer the long-term needs of the ISS until they become program critical, the committee recommends that NASA designate a senior ISS staff person to oversee implementation plans for post-Assembly Complete ISS operations, including the upgrades identified in the P^3I activity. This subject is discussed further in Chapter 5.

Recommendation. The National Aeronautics and Space Administration should designate a senior member of the International Space Station (ISS) staff to assemble, review, and approve budgets and implementation plans for post Assembly Complete, to facilitate improvements in ISS systems, and ISS operations, and to maintain a high degree of management visibility for this important activity.

The space station envisioned in the early 1960s could have been built with technology available at that time. As the committee noted in this report, the same is true of the ISS, which relies on existing technology and well established manufacturing techniques wherever possible. Therefore, the committee believes that the fundamental improvements cited in this report are well within the state of the art of current technology and should be introduced into the ISS Program as soon as possible. In the areas of communications and robotics, in fact, they have already been developed. With farsighted management and timely increases in funding, these upgrades and enhancements would ensure that the ISS remains at the leading edge of long-term space research.

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Introduction

This report documents the work of the National Research Council Committee on Engineering Challenges to the Long-Term Operation of the International Space Station. The report deals only with the postassembly phase of the International Space Station (ISS) Program (so-called "Assembly Complete") and not with the requirements for the assembly process. The substance of this report is based largely on information obtained by the committee from the National Aeronautics and Space Administration (NASA) and associated contractors between September 1998 and August 1999.

At the first meeting in September 1998, the committee reviewed the report of the Cost Assessment and Validation (CAV) Task Force of the NASA Advisory Council, which had been released several months earlier (CAV, 1998). The Terms of Reference for the CAV Task Force were compiled by NASA on October 14, 1997, concurrent with, and in direct response to, the congressional interest expressed in the Appropriations Act of October 17, 1997, that chartered this study. The CAV report was published in April 1998, just one month after the official start date of this study. The CAV report included a detailed review of the cost and schedule risks in the ISS Program. The report, which focused on the assembly phase of the program, predicted a one to three year schedule slip and a most likely date for Assembly Complete of December 2005.

For the operational phase of the ISS, the CAV report recommended a budget level of $1.5 to $1.6 billion per year, compared with NASA's goal of $1.3 billion per year. The task force concluded that the major budget risk factors during the operational phase would be replacing components due to equipment failures and obsolescence.

The committee found the CAV report to be a comprehensive and timely study of the ISS budget risks and decided that it need not be duplicated and that the study on the long-term operation of the ISS should be complementary to it. Therefore, the committee decided to focus on the engineering challenges of long-term ISS operations and delve into budget issues only if they were not covered in the CAV report. However, the CAV report covered the budget issues thoroughly and the recommendations in this report fit the CAV's budget assumptions for the operational phase.

NASA's goal of $1.3 billion per year for the operational period, beginning in fiscal year (FY) 2005, is a top-level estimate. The budget for that time period has not yet been developed in detail. Hence specific budget impacts could not be addressed in this study as they were in the CAV study, which included the initial five-year assembly phase.

Throughout this study, various committee members noted that the long-term operation of the ISS will constitute a major departure for NASA from its traditional mode of operation for human space flight operations. Until the Phase 1 Mir program, and with the exception of the three crew visits to Skylab in the mid-1970s, all of NASA's space flight experience has ranged from missions of several days to a few weeks. A major purpose of the ISS is to provide a platform for long duration microgravity experiments in the physical and life sciences. The ISS offers unique capabilities for research in the following areas:

- biomedical research and countermeasures system development (preventive measures for cardiovascular and musculoskeletal deconditioning)
- gravitational biology and ecology (under variable gravity)
- materials science
- biotechnology
- fluids and combustion
- human-machine interfaces and advanced life support systems
- low-temperature physics
- earth observation and space science

The following areas will be investigated on the ISS:

- the technologies best suited for long-duration human space exploration (NRC, 1996)

- the role of gravity in the evolution, development, structure, and function of life forms, and as a result of gravity, how life forms interact with their environment (NRC, 1998)
- the requirements for ensuring the health, safety, and productivity of humans living and working in space (NRC, 1998)
- the controlling mechanisms in cellular aggregation and differentiation for the *in vitro* growth of cells, organisms, organs, and other biologically interesting structures (NRC, 1995)
- the optimum relationship between the process used to form a material and its resultant properties, how this relationship can be achieved in space and on the ground, and how the space environment can help us obtain highly accurate fundamental physical measurements (NRC, 1998)
- the most effective energy conversion process involving combustion (NASA, 1998)
- the unique characteristics of fluid flow and heat and mass transfer in reduced gravity (NASA, 1998)
- the formation and evolution of the universe, galaxies, stars, and planets (NASA, 1998)
- the causes of change in the Earth environment over time (NASA, 1998)

The long-duration operation of the ISS will provide a new environment for research to answer these questions.

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International Launch Vehicle Fleet

The following brief review of the requirements for launch vehicles and how they will be met will provide a context for the committee's recommendations pertaining to the international launch vehicle fleet. A typical ISS launch support manifest for the operational phase after Assembly Complete is shown, by vehicle, in Figure 2-1. The ISS launch support requirements can be divided into three categories: (1) crew transport; (2) propellant resupply and ISS reboost; and (3) logistics.

CREW TRANSPORT

According to current plans, crew transport to and from the ISS will be provided by the Space Shuttle, the Soyuz, and the crew return vehicle (CRV). The Soyuz spacecraft will be launched by the Soyuz booster. The CRV will be carried to orbit by the Space Shuttle and will return either independently or in the Space Shuttle. Approximately five flights per year are planned for the Space Shuttle and two per year for the Soyuz. The CRV will have a three-year life on orbit attached to the ISS for crew return in emergencies. The Soyuz will provide this function until Assembly Complete and will also supplement the CRV throughout the operational phases of the ISS Program. At least every six months, the docked Soyuz will be replaced by a fresh Soyuz vehicle.

The European Space Agency is also evaluating a CRV that would be launched by Ariane 5 and would be capable of returning six crew members and/or experiment samples and equipment from the ISS. As yet, no budget or schedule has been established for the development of this vehicle.

PROPELLANT RESUPPLY AND REBOOST

Propellant resupply and ISS reboost account for more than half of the total launch mass requirement during the operational phase of the program. In the baseline plan, the reboost function will be filled by the service module, which will be resupplied with propellant by four Progress vehicles per year launched by Soyuz expendable launch vehicles. Because of uncertainties about the future availability of these vehicles, NASA has developed alternatives.

ALTERNATIVES TO RESUPPLY BY PROGRESS

The committee was informed that NASA's latest assessment of the availability of Progress vehicles indicates that only three launches per year will be available during the assembly phase of the ISS Program. Therefore, NASA has constructed and is implementing alternatives to ensure that the necessary propulsion and reboost capabilities will be available. The committee considered how these alternatives would carry over into the operational phase of the program.

NASA described the following three alternatives for dealing with the uncertainties in long-term Russian support of the ISS (McClain and Hawes, 1998):

- Option 1. Provide funding to Russia as necessary to complete and sustain all Russian contributions.
- Option 2. Provide funding to Russia for items necessary to continue the ISS Program in the near term while funding the U.S. capabilities (e.g., U.S. propulsion module) necessary to eliminate dependence on Russian participation, thereby establishing U.S. autonomy, in the long term.
- Option 3. Provide no funding support to Russia and adjust the schedule of the ISS Program, as necessary, to accommodate late Russian deliveries.

NASA has selected Option 2 as the "recommended" option, which would entail some funding of the Russian Space Agency for the following reasons:

- to maintain use of Russian Mission Control
- to maintain the schedule of the service module and ensure the availability of spare parts
- to maintain uninterrupted crew return capability via

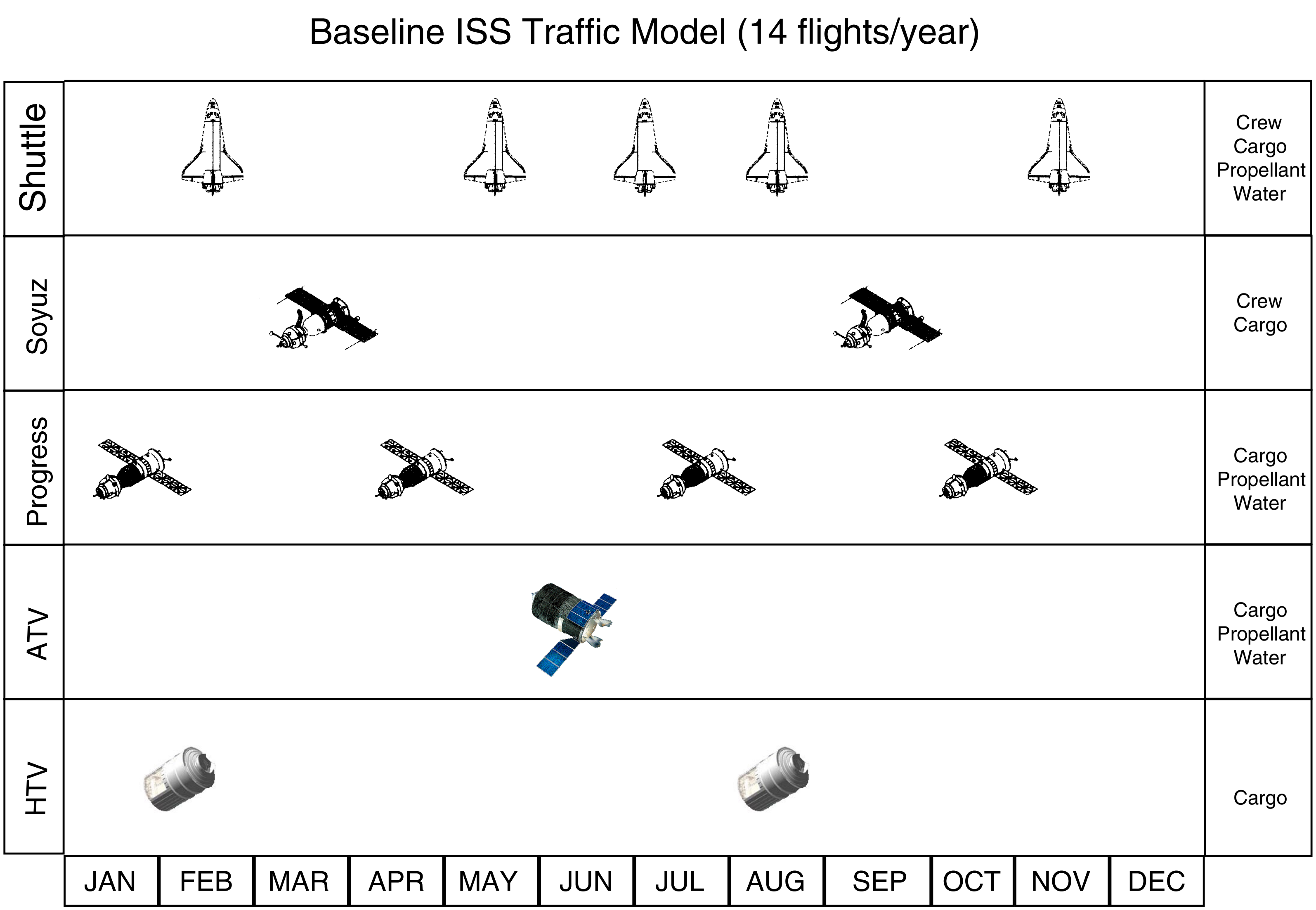

FIGURE 2-1 Baseline ISS traffic model. Source: NASA, 1999.

Soyuz until the CRV is available

- to retain Soyuz/Progress resupply vehicles until a U.S. propulsion module, autonomous transfer vehicle (ATV), and H-II transfer vehicle (HTV) are available

In the long term, Option 2 would establish the autonomy of NASA's ISS operations in the following ways:

- The Space Shuttle orbiters would be modified so that they could be used in place of Soyuz/Progress to resupply propellant (to reboost the ISS).
- A U.S. propulsion module would be developed for the ISS.

If Russian logistic support for long-term operations cannot be guaranteed, concerns may also arise about the long-term viability of critical Russian-built ISS components, such as the service module, which are permanent parts of the ISS.

Under the Option 2 scenario, the orbiters would be modified to provide propellant replenishment for a U.S. propulsion module, thereby supporting the long-term requirements for reboosting the ISS. Some of this propellant could be accommodated on Space Shuttle flights already planned for other purposes, if excess payload capability is available. However, because of the change in the location of ISS from a 28.5 orbit (minimum energy, due east launches from the Space Shuttle launch site at the Kennedy Space Center) to the higher 51.6 inclination (minimum energy, due east launches from the more northerly Soyuz/Progress launch site at Baikonur), the payload delivery capability of the Space Shuttle has been reduced to 13,600 kg (30,000 lbs) for flights to the ISS. Therefore, not many flights are likely to have excess payload weight margin. If Space Shuttle flights must be added to supply reboost propellant, the incremental cost of these additional flights should be a factor in NASA's comparison of Option 2 to the baseline operational mode (i.e., support by four Soyuz/Progress flights per year with no supplementary Shuttle flights required), even though NASA currently includes the ISS Shuttle flights in the Shuttle operations account rather than the ISS account.

The committee agrees that Option 3 should be rejected but is not convinced that Option 1 should be rejected in favor of Option 2. The choice involves a trade-off between cost and political considerations. The committee believes the cost to NASA might be lower if Option 1 were selected and funding were provided to enable Russians to meet their commitments. NASA did not provide a cost comparison or any other rationale for selecting Option 2. Therefore, the committee has no data to use as a basis for comparing the relative costs of Options 1 and 2.

Recommendation. The National Aeronautics and Space Administration should develop a concise comparison of Options 1 and 2 to document the relative costs, as well as the program risks and benefits, associated with implementing Option 2 in order to reduce International Space Station (ISS) dependence on Russia and achieve autonomy for the ISS Program in the long term. The cost estimates should include the following items:

- the incremental cost of operating the Space Shuttle to replace Soyuz/Progress logistics flights
- the cost of developing a U.S. propulsion module and delivering it to the ISS
- the cost and risk associated with integrating a U.S. propulsion module with the ISS this late in the ISS program
- other costs that may accrue in establishing U.S. autonomy
- risks to the program schedule

LOGISTICS TRANSPORT

Logistics transport will be provided primarily by the Space Shuttle at the rate of five flights per year, supplemented by approximately one flight per year by the European Space Agency's ATV launched by Ariane 5 and about two flights per year by the HTV (provided by the National Space Development Agency of Japan and launched by the H-II launch vehicle). The ATV will be able to dock autonomously with the service module, or by means of the space station remote manipulator system (SSRMS), to the ISS nadir port. In this location on the service module, the ATV's thrusters will be configured correctly to reboost the ISS. Neither the ATV nor the HTV is designed to survive reentry.

On the whole, the baseline plan for launch vehicle support of the ISS seems adequate, if it can be implemented. The wide variety of vehicles with different operational characteristics should add robustness to the program, a major improvement over a "Shuttle-only" supply system. However, as the committee was informed, the baseline has already been eroded because the original launch rate of six Soyuz/Progress flights per year after Assembly Complete has been reduced to four. There is no indication how long this shortfall will continue during the operational phase of the ISS.

CREW RETURN VEHICLE

The current plan for acquiring the CRV and operating it from 2003 to the end of the ISS Program seems adequate. The committee's understanding is that the CRV, which will be constructed under contract, will be based on a design developed by NASA reflecting experience with the X-38. The cost of development and construction of four vehicles is estimated at $580 million; the cost of CRV operation throughout the program is estimated at $187 million. Both amounts are included in current NASA budgets. The 2003 operational date for the CRV seems to be very optimistic, however, inasmuch as a prime contractor has not yet been selected. The CRV will have to be given a high priority to meet the ISS schedule.

The following specifications to which the CRV will be built are consistent with long-standing requirements:

- crew capacity of seven
- in the case of a need to evacuate the ISS (the capability to evacuate and depart the ISS in three minutes and return to Earth within nine hours
- in the case of medical emergency (the capability to return personnel to a medical facility on Earth within 24 hours of a declaration of need
- lifetime on the ISS of three years
- capability of holding in orbit for nine hours after separation from the ISS
- cross range of 450 nautical miles

The CRV mass is projected to be 12,700 kg (28,000 lbs). The vehicle will be carried to the ISS by the Space Shuttle and attached by the SSRMS. At the end of its three-year life on the ISS in a standby mode, the CRV can be carried down in the Space Shuttle payload bay or flown down either by remote control or, occasionally, with a flight crew on board. The CRV is designed to be used in an emergency, however, and does not have the system redundancy required to ensure safe repetitive operation in a piloted mode.

Recommendation. The National Aeronautics and Space Administration should proceed with the contractor selection/contract award process to start the flight system development and fabrication program for the crew return vehicle.

Recommendation. The National Aeronautics and Space Administration should evaluate returning the crew return vehicle (CRV) to Earth by remote control at the end of its standby period on orbit to develop experience with its systems, performance, and reliability and to increase the probability of a successful return from orbit in case of an emergency. Although this would entail an increase in cost from \$20 million to \$40 million because the propulsion system would have to be refurbished after flight, operating experience with the CRV in flight mode would support the development of a contingency plan in the event of a vehicle malfunction. The higher confidence level and flight experience with the system would justify the additional cost.

U.S. EXPENDABLE LAUNCH VEHICLES

A question that frequently arises is whether one or more of the U.S. expendable launch vehicles (ELVs) could be used to supplement the planned logistics support vehicles for the ISS. At present, NASA has no plans to do so. Ten assessments in the past eight years by different NASA groups have consistently shown that overall ELV mission costs would be higher than those of the Space Shuttle or of foreign ELVs (Poniatowski, 1999). Therefore, NASA has concluded that it would be less costly to use one of the logistic modules currently under development by the international partners (i.e., the ATV or the HTV) than to use an ELV.

The recommendations from the NASA *Space Transportation Architecture Study*, which focuses on meeting NASA's future space transportation requirements at reduced costs, advocates the development of technology for the next-generation reusable launch vehicle (RLV) as a replacement for the Space Shuttle. The NASA study also recommends that a next-generation crew and cargo transfer vehicle (CCTV) be defined. The CCTV could be launched either by an RLV or an enhanced expendable launch vehicle (EELV). Phase 3 of the NASA study will determine whether the reliability of an EELV would be equal to, or better than, the Space Shuttle. These studies will eventually determine the future course of the CCTV and RLV programs and will define their role in supporting the long-term operations of the ISS (Mulville and Freeman, 1999).

ASSURED ACCESS TO THE ISS

The reliability of the national and international launch systems for supply, operations, and maintenance of the operational ISS must be considered in the context of overall space transportation resiliency and operability (i.e., the ability of the mixed fleet and associated propulsion systems [Soyuz, Space Shuttle, Ariane/ATV, CRV, U.S. propulsion module, and others] to ensure access to the ISS and to ensure the continued viability of the system as an orbiting platform). Both the Soyuz booster and the Space Shuttle are rated for human flight and have demonstrated very high reliability. The CRV and the U.S. propulsion module are undeveloped flight systems that have no record of space flight; hence their reliability and robustness are not known. Although problems during early development may delay the full operational capability of these new space flight systems, their reliability levels ultimately are likely to be comparable to those of the Soyuz and the Space Shuttle.

High reliability will reduce, but not eliminate, the potential of a launch vehicle being unavailable. If the mixed fleet is international, the availability of a launch vehicle will be a function not only of its reliability and stand-down time in case of a failure, but also of political considerations. In addition, if launch systems are vying for commercial business, their availability may also be a function of commercial launch priorities and scheduling considerations that are different from ISS priorities and requirements. In other words, they may be committed elsewhere.

In a worst case scenario, Soyuz/Progress flights would have to be replaced because of a stand-down. The most straightforward solution would be to fill the gap with additional Space Shuttle flights. Because the Soyuz/Progress would normally fly four flights per year, but with substantially less cargo-carrying capability than the Space Shuttle, several Space Shuttle flights could probably replace the four Soyuz/Progress flights (with some adjustments to the Shuttle mission manifest). NASA has concluded that, in the event that Progress is unavailable, the Shuttle could perform the reboost function and that the propellant reserves aboard the ISS could provide the attitude control functions for one year or more.

A significant problem would develop, however, if a Space Shuttle stand-down occurred at the same time as the Soyuz/ Progress stand-down. The seriousness of this situation would depend on the duration of the concurrent stand-down of the vehicles. In this case, crew safety and return would be ensured by a CRV. The combination of the unavailability of Soyuz/Progress, a concurrent Space Shuttle failure, and a concurrent failure of the CRV is considered highly unlikely. Thus, NASA's planning is presently focused on maintaining the normal operations of the ISS in orbit and the timely development and flight certification of the CRV.

ROLE OF THE INTERNATIONAL LAUNCH VEHICLE FLEET

If both the Space Shuttle and the Soyuz were in a stand-down mode concurrently, support of ISS crew operations would no longer be possible. If Soyuz were unavailable for one year, there is about a 10 to 20 percent chance that the Shuttle would also become unavailable during that time (based on 0.99 and 0.98 probability of success per flight, respectively, and 10 flights during this period).

Other vehicles, particularly the ATV (propellant logistics) and the HTV, are part of the ISS logistic support baseline and could be used for noncrew-related logistics operations. The ISS can survive without a crew, and the ATV can dock without a crew. The contingency plan for the concurrent stand-down case, therefore, is to evacuate the crew and to "mothball" the ISS by moving it to a higher orbit and providing propellant replenishment via the ATV, thereby prolonging its life and reducing logistics flight requirements.

Although some other launch vehicles are currently operational (e.g., Atlas, Delta, Proton, Sea Launch, etc.) and some are under development (e.g., EELV, Kistler, X-33/ VentureStar, etc.), the use of other ELVs has not been seriously considered (those under development cannot be seriously considered until they become operational). Private-sector funding for a new launch vehicle that meets ISS requirements appears to be unlikely without a significant government subsidy. No agreements have been reached with Arianespace to pay for the use of the Ariane launch vehicle to support ISS operations, and no launch priorities have been discussed. NASA suggests that a barter arrangement could be worked out in the event that emergency ISS support was requested.

Recommendation. The National Aeronautics and Space Administration (NASA) should develop contingency planning for personnel transport and resupply during the operational phase of the International Space Station (ISS). The assessment should identify viable options other than moving the ISS into a high storage orbit in case of a concurrent stand-down of the Space Shuttle, the Soyuz, and the Soyuz/ Progress vehicles. NASA's plan should accommodate new launch vehicles that may become operational during the operational lifetime of the ISS for both crew transport and ISS resupply. The plan should address the relative costs of the various options for ensuring access to the ISS.

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3

Operations, Maintenance, and Reliability

A major purpose of the ISS is to provide a platform for long-duration microgravity experiments in the life sciences and physical sciences. ISS operational principles, maintenance requirements, the reliability of hardware and software, and the ability of onboard crews to work efficiently will directly affect the achievement of this goal. This chapter provides suggestions to NASA for ensuring the success of long-term ISS operations.

DAILY FLIGHT CREW SCHEDULING

ISS crews will have full daily schedules on board the station: they will support the day-to-day operation of the station; they will perform maintenance of ISS systems and laboratory equipment, make repairs to ISS systems and laboratory equipment, and conduct scientific research and manage experiments; and they will need time for regular exercise and periods of rest. Careful planning will be necessary to ensure a balance so that one set of priorities, such as maintenance and repair, does not conflict with others, such as scientific research or experiment management. NASA's traditional methodology for scheduling the day-to-day activities of the flight crew was appropriate for short-duration space flights. However, experience with long-duration space flights on Skylab and Mir suggests that a different approach would ease the pressure on the daily timeline and ensure that the crew has time for scientific research.

To capitalize on the full potential of the new environment provided by the ISS (i.e., the ability to operate in space for extended periods of time), NASA should consider transferring some control of day-to-day scheduling details to the crew on board the ISS. The idea is to capitalize on the crew's unique experience with the on-orbit laboratory and to permit the crew to organize their tasks in the most time-efficient manner. For example, the mission control center could provide the crew with objectives for the upcoming week, including a summary of the science and a proposed timeline. The crew could then make adjustments to the timeline, send them to the ground, and the ground controllers would follow the crew's suggestions without requiring justifications for each change. This would rely on the crew's extensive knowledge of their space laboratory to optimize the order in which activities were performed and adjust the time required to perform specific tasks. The detailed crew-developed timelines would be subject to periodic progress reviews with the ground controllers to ensure that the overall objectives for that crew's increment aboard the ISS were being met (an "increment" is the duration of a particular crew's stay aboard the ISS, the period between crew rotations). Ideally, this arrangement would leave more time for research by allowing the crew to optimize their daily schedule and recover time otherwise committed to standard blocks of time for maintenance and repair tasks and station operations.

Recommendation. The National Aeronautics and Space Administration should allow the International Space Station (ISS) crew on orbit to contribute to the development and optimization of the daily timeline. The time saved would allow the crew to devote more time to scientific research. Oversight of the accomplishment of crew tasks aboard the ISS should be maintained by mission control through periodic flight crew/ground controller progress reviews.

ONBOARD MAINTENANCE

In briefings to the committee, the committee learned that the crew would be trained both to work on experiments and to perform "routine" maintenance on the station. The crew would also be able to do some troubleshooting of hardware and make some minor repairs. Tasks that require extravehicular activity (EVA) will be performed by Space Shuttle crews as much as possible (Harbaugh and Poulos, 1999).

Plans call for ISS crews to spend some time conducting research on behalf of the principal investigators (PIs) and some time performing routine maintenance. However, the committee believes, based on Phase 1 Mir experience, that the crew may also have enough time to accomplish some of the day-to-day mission operations and thus reduce the aggregate requirement for ground personnel. A reassessment of the crew timelines might reveal that they could perform some of the work now planned for mission controllers on the ground. To that end, NASA should prepare a long-term "design reference mission" showing projected clusters of crew activities against a timeline. It would be useful, for example, to show a typical 30-day timeline with the Space Shuttle docked either at the beginning or the end of the 30-day period. This would help determine if measures to increase onboard crew efficiency and conserve the crew's working time will be necessary. NASA did provide the committee with copies of the *Concept of Operation and Utilization Mission Scenarios and Mission Profiles*, which documents this type of timeline planning for Space Station Alpha (NASA, 1994). That document, however, has not been updated since 1994 and the timeline scenarios are not being continued in the ISS Program.

Recommendation. The National Aeronautics and Space Administration should reassess the crew's activities against a more realistic timeline based on the Phase 1 Mir experience, as well as experience gained during assembly of the International Space Station. If the crew could take on more of the day-to-day mission operations, the aggregate requirements for ground crew personnel would be reduced.

Recommendation. Maintenance onboard the International Space Station (ISS) should be scheduled during resupply missions as much as possible. Resupply missions are also the preferred times for conducting extravehicular activities because the microgravity environment will already have been disturbed by the resupply vehicle docking with the ISS. If the Space Shuttle is the resupply vehicle, additional personnel will also be available to help with maintenance tasks during docked operations. Cooperative tasks between the arriving crew and the departing crew will also facilitate the passing of detailed information to the arriving crew (the so-called "crew handover").

STAFFING OF THE OPERATIONS CONTROL CENTER

Current flight and ground control operations are understandably focused on the ISS assembly processes, planning for EVAs, training, testing flight hardware, and planning logistics. NASA personnel who briefed the committee expressed the concern that this intense activity could lead to burnout of ground support personnel. The Phase 1 Mir experience shows that work/rest cycles are important for ground personnel and for the productivity of the long-duration mission. Chronic fatigue from working long hours and extended work weeks result in an increase in incidence of illness, loss of performance, and team member attrition (NASA, 1998a). In support of Mir operations, the Russian practice has been to maintain only a small team in the mission control center and have experts on call to support them whenever necessary. New information technologies could enable NASA to go one step further by establishing remote workstations, which would allow people to focus on solving problems and rely on support software to identify problems. Although problems can occur at any time, experts "on duty" at their homes or offices could have on-line access to the data and analysis tools necessary to enable them to work with the smaller mission control center staff to prioritize and resolve problems with the help of support software and on-line displays.

NASA's current plans for flight and ground control operations are concentrated on the ISS assembly flights and are based on the fully staffed, "all-up" mission control center philosophy that has been used by the U.S. space flight program since the days of Mercury, Gemini, and Apollo and has been continued for the Space Shuttle program. Almost none of these operations, however, lasted more than two weeks. NASA has acknowledged that the new operational environment of the ISS (i.e., continuous operations in support of a very long-duration mission) and the intense continuous activity might eventually cause burnout of ground support personnel (Harbaugh and Poulos, 1999). The safe reduction in on-site mission control staff is also essential to the long-term fiscal soundness of the ISS program. NASA has not yet addressed the challenges associated with optimizing the long-term operation of the ISS.

Recommendation. The National Aeronautics and Space Administration (NASA) should develop a new concept of operations for the long-term operation of the International Space Station that includes the integration of new information technologies into mission control center processes. NASA should consider adopting the Russian operational practice used for Mir (i.e., maintaining a small team in the mission control center and relying on experts on call with remote access to the data and personnel in the mission control center).

COMMUNICATION WITH PRINCIPAL INVESTIGATORS

For the long-term operation of the ISS, NASA has an opportunity to reinstate some of the procedures that were used for Spacelab, when the crew was allowed to communicate directly with the PIs instead of having to coordinate responses through the ground support team. NASA's traditional practices worked well for short-duration space missions, but with new communication technologies and long-duration space flight, NASA could consider allowing crew members to communicate directly with PIs on questions of science, experiment protocol and experiment status, and other subjects that do not affect the operation or safety of the ISS. Direct communication would be more efficient, would result in better science, would lead to significant time savings for both the crew and the ground support team, and would ease the pressure on the crew's daily timeline, giving them more time to perform research.

During Phase 1 operations on Mir, the Russians were able to take advantage of direct communications between PIs and crew members. This approach saved the crew time and provided them with answers directly from the experts. If a crew member had further questions, the PI could respond immediately. For the long-term operation of the ISS, direct communication would be efficient and would greatly enhance the crew's ability to support experiment protocols and scientific objectives.

Recommendation. The National Aeronautics and Space Administration should adopt the practice demonstrated during the Mir program of direct communications between the crew and principal investigators (PIs). Crew members and PIs should be able to exchange data and instructions to enable the crew to carry out experiments in the way that best fulfills the goals of the experiment. Computer links should be developed and communications systems upgraded to provide real-time assessments of the data and the capability of responding to change.

Recommendation. The National Aeronautics and Space Administration and the scientific community should explore ways to enable principal investigators to access their experimental data directly from ground locations at universities and research facilities to increase the direct involvement of the science community in ISS experiments.

PAYLOAD SPECIALIST

NASA's projected requirements for the ISS crew do not include a payload specialist. The payload specialist program worked very well on Spacelab missions on the Space Shuttle. The payload specialist was in a unique position to make significant contributions to the quality of science and the success of experiments.

Because some very precise experimentation will be performed on the ISS, having a scientific expert onboard would increase the quality of support available to the PI. The payload specialist could make *in situ* adjustments to experiments that might otherwise require time on the ground to analyze results and, perhaps, require reflight of the experiment. The payload specialist would also be able to provide early warning of the need to change or upgrade experimental equipment.

Recommendation. The National Aeronautics and Space Administration should reassess its crew requirements for the International Space Station and consider including a payload specialist in the seven-person crew.

CREW HANDOVER

NASA has not developed a plan for on-orbit handover to ensure that efficiency is maintained and no errors are introduced that would result in costly reworking or increase operational risk. Every effort should be made to capitalize on the knowledge of the departing crew members. The value of a smooth, efficient handover is well documented by the Mir experience (NASA, 1998a).

Mission planning could allow Space Shuttle crew members to perform many joint tasks during the handover period. Ideally, crew members would have all of the docked time for the handover. Although this may not always be possible, it should be established as a goal to help mission planners establish priorities. During the handover period, the new flight crew can become familiar with the protocols of ongoing experiments through actual operations under the guidance of the departing crew.

Recommendation. The National Aeronautics and Space Administration (NASA) should develop a plan and process to ensure that crew members on board the International Space Station have as much time as possible for their on-orbit handover during docked operations. The handover should be formal and should include essential hard copy and/or laptop computer files of historical records to ensure that arriving crew members have a complete understanding of activities in progress before returning crew members depart. In developing the handover plan and process, NASA should assess the desirability of performing critical maintenance tasks during Shuttle handover periods to take advantage of the availability of additional crew members.

ONBOARD FAILURE DETECTION AND CORRECTIVE ACTION

On-orbit maintenance includes the detection of an anomaly, the identification of the failed orbital replacement unit (ORU), and replacement of the ORU or creation of a work-around. The first two of these activities are very difficult to plan and train for comprehensively because failures are often unpredictable. Localization of a failed component is essential for the efficient functioning of the ISS. The most successful way to localize failures is for each ORU to be responsible for its own failure monitoring, with backup monitoring at the system level. The starting point for the process is usually the failure modes and effects analysis (FMEA), which is generated as part of reliability assessments. The FMEA made available to the committee was focused on safety-critical items but did not address overall maintenance. The methodology supporting this approach is referred to as failure detection, isolation, and recovery (FDIR). In the ISS context, FDIR has two meanings: (1) software programs for the automated detection of failures and identification of the failed units *and* (2) the overall process of which the software programs are a part.

Only one individual is presently responsible for management oversight of the FDIR software program at the NASA Johnson Space Center. Overall failure identification is being investigated by Boeing as part of the Launch Package and Stage Assistance Program (Wolf, 1999). Neither of these is directly connected to the FMEA generated by the reliability and quality assurance organization, and neither addresses the need for training, providing spare parts, or other logistics. The committee could not determine if failures in monitoring circuits, which might lead to the unnecessary removal of an ORU, have been considered by the ISS Program.

The stated goal of the FDIR is to achieve 90-percent identification to a single ORU; 95-percent to two ORUs; and 98-percent to three ORUs. This goal appears to be unrealistic in light of the limited efforts NASA has devoted to FDIR to date. No plans for verifying these levels of identification were provided to the committee. Considering the importance of FDIR for the efficient long-term operation of the ISS, the lack of attention to this activity is an indication of NASA's focus on the assembly phase of the ISS to the exclusion of important operational considerations and contingency planning for its long-term operation.

Recommendation. The National Aeronautics and Space Administration should greatly expand its focus on failure detection, isolation, and recovery (FDIR) in conjunction with the failure modes and effects analysis (FMEA). The following issues should be addressed specifically:

- allocation of responsibility to automated/nonautomated functions
- consistency of the FDIR with known failures
- integration with space and ground crew training and logistics

SAFETY, RELIABILITY, AND MAINTAINABILITY PROGRAM

The safety, reliability, and maintainability program (SR&M) follows policies established by the NASA Headquarters Office of Safety and Mission Assurance (Code Q) and meets the conventional requirements of SR&M programs. In examples furnished to the committee, areas that impact safety had been analyzed in depth. Nevertheless, the committee found no evidence that NASA had taken into account the aggregate of interfaces in the ISS and the heavy dependence on software. NASA's approach is not proactive in that it has not identified early, small expenditures for improvements in SR&M that could avoid the eventual high cost of failures.

The SR&M program would benefit from more trend analyses of all data that could have a bearing on the long-term failure rate, maintenance capabilities, and spare parts requirements of the ISS. The Hubble Space Telescope (HST) program, for example, now considers "trending" as its primary SR&M analysis method.

Trend analysis for the ISS could include the following elements:

- incoming inspection reports
- in-process test reports
- failure reports from on-orbit segments
- maintenance records for ground and on-orbit operations

Recommendation. Analyses of the incoming inspection and in-process testing data should be used to establish a six-sigma environment in which failures will be extremely rare. Analyses of failure reports and maintenance records should be used to improve on-orbit procedures and the quality of replacement items.

SPARE PARTS PHILOSOPHY

NASA provided the committee with information on plans to provide spare parts and logistics for the ISS (NASA, 1998b). The committee also reviewed the same information for the HST, the only other long-duration U.S. space vehicle that has involved crew servicing. The opportunities for component replacement on the ISS and the HST differ—four or five visits per year for the ISS and three or four years between visits for the HST. In terms of manufacturing lead-time for producing spare parts, however, the biggest difference is that significant lead-time is available between repair visits to the HST to secure replacement parts.

For the HST, solar panels, mechanical relays, and rotating devices (e.g., wheels, gyros, gimbals, and servos) were stockpiled, but in HST's nine years on orbit, the electromechanical devices and the purely electronic devices have had only moderate failure rates (Styczynski, 1999). Experience with the HST project revealed that NASA could not afford to stock and maintain the extensive depot facilities and the large numbers of spare parts required for the HST based on the "old" measure of statistical mean time between failures of the hardware (Kelley, 1999). Another method of providing spare parts would be to introduce upgrades during the operational life of the ISS to reduce failure rates and thereby reduce maintenance requirements (this concept is discussed further in Chapter 5).

NASA's current philosophy of providing spare parts for the ISS requires a very large contingent of personnel and extensive facilities. Because the ISS is expected to have a nominal operational lifetime of 15 to 20 years after Assembly Complete, the project would require repair and maintenance depots, as well as inventories of spare parts. As the HST experience has shown, however, predictions of the requirements for spare parts are not accurate. The combination of inaccurate predictions and the possibility of technological advances and evolving requirements of ISS operations suggests that NASA could adopt a less conservative approach except for items essential for life support.

Recommendation. The National Aeronautics and Space Administration should reassess its current philosophy for providing spare parts, as well as the depots and associated personnel required to maintain them for the operational International Space Station (ISS). The criticality of hardware, wear-out factors, and the potential for subsystem upgrades should be considered in the reassessment. The logistics, reliability, and mission assurance personnel for the ISS should establish an ongoing liaison with their counterparts in the Hubble Space Telescope program to evaluate a new philosophy for the ISS and the possibility of reducing associated costs.

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4

Extravehicular Activity, Robotics, and Supporting Technologies

EXTRAVEHICULAR MOBILITY UNIT AND EXTRAVEHICULAR ACTIVITY TOOLS

The extravehicular mobility unit (EMU) is an anthropomorphic crew enclosure made up of two major subassemblies: the space suit assembly (SSA) and the life support system (LSS). The SSA consists largely of soft goods, with one major exception, the hard upper torso (HUT), a vest-like fiberglass structure that forms the central part of the SSA. The arms, helmet, lower torso, and LSS are mounted on the HUT. The LSS contains a primary life support subsystem (PLSS) and a backup purge flow system, the secondary oxygen package. The EMU allows the EVA crew member to work outside the ISS free of umbilicals to the spacecraft. It is pressurized to 29.6 kPa (4.3 psia), supplies oxygen, removes carbon dioxide, rejects metabolic and environmental heat, and removes moisture from perspiration and exhaled breath. The EMU, which has been called a one-person spacecraft, is made up of more than 100 major components.

In addition to NASA's EMU, the Russian "Orlan" space suit will also be used on the ISS (Poulos, 1999). Although this will provide redundancy, the complexity of maintaining and operating two separate systems that provide essentially the same basic EVA capability will double the requirements for resources and funding.

The current Russian space suit used for EVAs on the Mir is a derivative of the semirigid suit used during the Salyut-Soyuz program. This suit, the "Orlan-DMA," is the fourth generation model of the space suit. The Orlan DMA and the American EMU are similar in many ways. The Orlan-DMA space suit has an integrated life support system to enable EVA operations. The suit can be adjusted for size and has a metal upper torso and fabric arms and legs. The metal ball bearings and sizing adjustments are notable features. The Orlan-DMA has redundant, self-contained, integrated, pressurization and oxygen supply systems in a backpack-type PLSS that can be maintained on orbit. The oxygen supply system includes reserve oxygen storage and equipment for controlling and maintaining the pressure. The ventilation system and environmental gas composition-control system include removal units for carbon dioxide and contaminants, as well as gas circulation-control equipment. The space suit has no umbilical lines. Oxygen, water supplies, pumps, and blowers are located inside the rear hatch. Unlike the EMU, which is a waist entry suit, the Orlan-DMA is donned through a rear hatch. Unassisted entry requires only two to three minutes.

Most of the tools in the large inventory of ISS EVA tools were designed to meet the needs of crew members performing specific tasks. Tools are reused for other tasks only if mission similarity allows and if crew safety and productivity are not compromised. The current inventory includes 200 different part numbers and more than 4,000 parts stored in four separate storage areas. NASA is planning to store all of the tools for the ISS in a centralized, ground-based storage area under the control of United Space Alliance. Efforts are also under way by EVA planners to develop standardized tools to reduce training time as ISS EVA training evolves from task-specific training (the mode of operation during ISS assembly) to skills-based training (the mode of operation after ISS Assembly Complete) (Harbaugh and Poulos, 1999).

During the assembly phase of the ISS, unprecedented demands are being placed on both NASA and contractor personnel and facilities. For example, during the four years of ISS assembly, 1,600 hours of EVA are planned. Compare this to the 543 hours (90 EVAs) during the first 15 years of the Space Shuttle program. This three-fold increase is known as "the wall" of EVA (Figure 4-1). The ISS assembly demands will place significant stress on personnel and processing/training facilities, and the potential burnout of skilled people and shortage of facilities represent increased risks to the program (Poulos, 1999). During the ISS operational phase, NASA projects that there will be 20 EVAs (i.e., 120 EVA hours or 240 crew hours) per year.

Training for ISS assembly and training for ISS operations are fundamentally different. Because components are added to the ISS in a rigorously planned assembly sequence, an assembly task is a choreographed event that requires task-based training. The motions of the astronauts, the robots, and the assembly pieces are not only thoroughly planned, they are also exhaustively rehearsed. The vast majority of training takes place in the Neutral Buoyancy Laboratory at the Johnson Space Center, and the environment in which the EVA task is performed is controlled and well understood. Extensive underwater EVA training is well accepted by the crews as a prerequisite for safe EVA.

A maintenance or repair task during the operational phase of ISS is much more likely to be a skill-based task than a preplanned, rehearsed task. Although an astronaut could be trained for a "standard" ORU changeout, he or she cannot be trained in anticipation of all possible failures. Even if an astronaut were trained for a specific maintenance scenario, the training would not remain current indefinitely. Unlike Shuttle EVA crew members, the ISS crew may have to use procedures long after the training period, relying on memory. Therefore, there will probably be some loss in proficiency, especially for repairs late in a flight increment. Unscheduled repairs will necessarily be performed on structures that are already assembled, when access to a damaged component may be much more difficult than during assembly. Therefore, astronauts performing EVA repair tasks will necessarily rely heavily on their skill-based EVA training and standardized tools.

On-orbit training could be an effective way to meet the needs of astronauts who must rely on skill-based EVA training to perform unpredictable maintenance and repair tasks. On-orbit training would be based on real-time communications between support personnel on the ground and the EVA crew on orbit to walk them through and discuss potential EVA tasks. Real-time communications would require high bandwidth communications systems.

On-orbit training could also be accomplished asynchronously, with the EVA crew relying on appropriate training materials and equipment on board, rather than on the ground (i.e., on-orbit CD-ROMs, videos, models and mock-ups) augmented by suggestions from mission control. With task-specific on-orbit training, the crew could be trained for a specific task(s) immediately before an EVA (a practice that was used onboard Mir). On-orbit training would require meticulous planning to ensure that all of the necessary equipment and capabilities were aboard the ISS including: adequate computer simulation; high bandwidth communications; and accurate physical or digital models that can be reconfigured and updated as the ISS evolves.

Virtual-reality training, a comprehensive form of asynchronous training, has proved to be a useful complement to underwater training and has the potential to enable more extensive on-orbit training protocols in the absence of the neutral buoyancy facility. The training ratio for Shuttle EVAs has historically been in the range of 10:1 (i.e., 10 hours of neutral buoyancy training for each hour of actual EVA). Training for maintenance EVAs after Assembly Complete is expected to be in the range of 3:1 for neutral buoyancy training when augmented with virtual-reality training (Harbaugh and Poulos, 1999).

Recommendation. The National Aeronautics and Space Administration (NASA) should implement a plan to shift from current training procedures to a combination of skill-based training on the ground and task-specific training on orbit. NASA should plan for and develop an extensive on-orbit training program for rehearsing, simulating, and creating optimal extravehicular activity performance and timelines. The materials and equipment associated with on-orbit asynchronous training should be integral elements of the ground-training program so the crew can become familiar with the CD-ROM and video approaches to training before being required to use them on orbit.

PREBREATHE PROCEDURES

The purpose of prebreathe procedures is to decrease the potential for decompression sickness (bends) incidents associated with EVA. The current procedures are based on those used to prepare for Space Shuttle EVAs. The Shuttle depressurizes the cabin pressure from 101.3 kPa to 70.3 kPa (14.7 to 10.2 psia) for 24 hours prior to a scheduled EVA, and the EVA crew prebreathes pure oxygen for two hours prior to depressurizing the EMU to 29.6 kPa (4.3 psia). Unlike the Shuttle, the entire ISS cannot be depressurized. Therefore, the EVA crew is placed in the airlock, which is depressurized to 70.3 kPa (10.2 psia) overnight, the so-called "camp-out" procedure. The crew then prebreathes pure oxygen for four hours prior to depressurizing the EMU to 29.6 kPa (4.3 psia) at the start of the EVA. This entire procedure is time consuming and severely restricts the EVA crew's activities during the period.

NASA has been studying methods of shortening the prebreathing period. For example, current test results suggest that exercise during the pure oxygen prebreathe period can reduce the prebreathing time without increasing incidents of decompression sickness. The target prebreathe period is one to two hours (Poulos, 1999).

Recommendation. The National Aeronautics and Space Administration (NASA) should continue its ground-based development program to reduce the risk of bends incidents in extravehicluar activities (EVA). NASA should also develop and fly instrumentation that will aid in the early detection of the onset of bends incidents (e.g., an improved in-suit Doppler, a system to acoustically measure the presence of gases in the bloodstream). NASA should continue its efforts to reduce the time required for prebreathing so that the procedure can be accomplished during the period of several hours required for other EVA preparation and checkout activities.

SPACE SUIT UPGRADES

U.S. System

The EMU was designed and certified to meet the needs of the Space Shuttle crew and has been used since 1983. For the extended on-orbit operational life required for the ISS, the robustness and durability of the EMU have been improved by a comprehensive enhancement program conducted during the 1990s resulting in the recertification of the EMU for use on the ISS. All indications are that the current Shuttle/ISS EMU can meet the requirements of the ISS operational phase (Poulos, 1999). Nevertheless, although the electronic components of the EMU have proven to be reliable and durable, they were designed between 1979 and the mid-1980s, and many of the electronic parts have become obsolete and are no longer in production. Because vendors no longer manufacture these parts, NASA's contractor has had to search for the limited quantity of parts that remain in distributor inventories and secure funding from NASA to procure them to reduce near-term risks (Francis, 1999). The contractor has proposed redesigning the EMU electronics using components based on current technology that would be usable for both the Space Shuttle and the ISS until the end of the program in 2020.

Recommendation. The National Aeronautics and Space Administration should continue to search for and acquire electronic parts to support the current extravehicular mobility unit (EMU) to reduce near-term risk and should redesign the EMU electronic components using current technology to satisfy the long-term EVA needs of the International Space Station.

Logistics and Resupply

NASA and the EMU contractor continue to monitor EMU supply and the demand created by the combined Space Shuttle and ISS programs. The goal is to meet a probability of sufficiency of 90 percent for the LSS and 80 percent for the SSA. Because of projected shortages of the LSS, NASA is considering procuring one additional PLSS and one additional secondary oxygen package. In addition, the PLSS certification test hardware is being considered for upgrade to full flight status by NASA (Crew and Thermal Systems Division, Johnson Space Center).

The SSA has significantly shorter lead-time than the LSS and therefore can be dealt with in a shorter turnaround time. However, the SSA components must be available in a variety of sizes to fit a variety of crew members.Therefore, an inventory of SSA components will be required.

An analysis of LSS and SSA supply and demand reveals that shortages could prevent the program from meeting the goals of probability of sufficiency of 90 percent for the LSS and 80 percent for the SSA. The projected shortages, combined with the need to support unplanned contingencies, are likely to cause launch delays during ISS assembly, as well as delays in EVAs during the ISS operational phase.

Recommendation. The National Aeronautics and Space Administration should procure additional Life Support System hardware, and/or upgrade the Crew and Thermal Systems Division's Life Support System certification hardware and should procure additional hard upper torsos and space suit assembly hardware and soft goods.

Russian System

Russian research and development is focused on improving suit performance (specifically mobility), decreasing the payload weight required to replenish space suit consumables, extending operating life, and using microprocessors to control and monitor space suit systems. Payload weight required to replenish consumables might be reduced by regeneration of carbon dioxide absorbers, removing heat without evaporative water loss, decreasing oxygen leaks, and using advanced oxygen supplies.

RELIABILITY OF THE SIMPLIFIED AID FOR EXTRAVEHICULAR ACTIVITY RESCUE (SAFER)

The simplified aid for EVA rescue (SAFER) was designed as the last line of defense for an EVA crew member who has become detached from the ISS. Crew members are normally attached to the ISS by a series of redundant tethers. The SAFER, which is attached to the EMU LSS, is an emergency return system that provides a fly-back capability in the event that the tether system fails. SAFER uses a stored gaseous nitrogen propulsion system that expels gas through 24 thrusters. SAFER operation is initiated by activating a pyrotechnic valve to initiate the flow of nitrogen through a regulator to the thruster nozzles. Gas flow is controlled to provide a velocity of up to 3.05 m/s (10 fps).

The Space Shuttle has the capability of maneuvering to retrieve a detached EVA crew member, but the ISS does not. Because the ISS will be operating for more than a decade, and because hundreds of EVAs will be conducted over its lifetime, the SAFER must be absolutely reliable. Early operational evaluations of the system, however, have revealed failure modes that could compromise crew safety. The SAFER is not a "single-fault-tolerant" system, and certain failures render it inoperative.

Recommendation. The National Aeronautics and Space Administration should ensure that the simplified aid for EVA rescue (SAFER) is a completely reliable, single-fault-tolerant system.

ROBOTIC SYSTEMS

The complement of robotic devices on the ISS will include the mobile servicing system, with the SSRMS (ISS remote manipulator system) and the special purpose dexterous manipulator (SPDM), the European robotics arm (ERA), and the Japanese experiment module (JEM) robotics system. The SSRMS and SPDM are the primary devices that will be used for both assembly and maintenance of the station. The ERA will be used during assembly of the Russian science power platform; the Japanese robotics system will be used to service external payloads on the JEM exposed facility.

The SSRMS is a large arm capable of maneuvering and berthing major components of the ISS. It also provides a platform from which an astronaut can perform EVA tasks or be transported to other EVA work sites. The SSRMS can also transport the SPDM, a dual-arm robot designed to perform ORU changeout. Approximately 200 (out of a total of 600) ORUs on the ISS have been designed to be compatible with the SPDM. The three interfaces for handling ORUs are: a microconical fixture; a microfixture; and an H-fixture. The SPDM can also be used to perform a few tasks that do not involve specialized fixtures (e.g., opening doors that cover ORUs).

The primary mode of operation of the SSRMS and SPDM is joint-controlled teleoperation. In this mode, an astronaut controls each joint of each arm directly, issuing joint motion commands based on what the astronaut observes by looking at the arm. This is an effective but limited control technique that requires great skill and extensive training.

NASA has a well developed plan for assembly of the ISS based on the capabilities of the existing suite of robotic systems (SSRMS and SPDM) and the skills of the EVA astronaut. Although new robotic technologies could increase the safety and/or productivity of the astronaut-robot team, new technology will not be necessary for the completion of ISS assembly. Therefore, the NASA team has adopted an approach based largely on well proven, existing technology that mitigates much of the risk and expense of developing and applying new technology.

NASA's plan for using robotic devices for the maintenance and servicing of the ISS after Assembly Complete is not as well developed. In fact, a compelling case can be made for incorporating new robotic technology in this phase of the program. Many maintenance and repair tasks will be fundamentally different from assembly tasks, and preparation for these tasks will require skill-based training rather than task-specific training.

During ISS assembly, astronauts receive training and practice robotic arm tasks just prior to each mission. Therefore, the training and practice are recent and fresh when the task is undertaken on orbit. After Assembly Complete, however, significant time may elapse between training on the ground and the actual execution of robotic arm operations. Thus, an astronaut's proficiency with the SSRMS/SPDM after Assembly Complete is likely to deteriorate with time. After ISS Assembly Complete, the crew may also be called upon to perform tasks that they have not specifically practiced.

Improvements to the systems used to control the SSRMS/SPDM would be very beneficial after Assembly Complete, and some technologies that could be incorporated on the SSRMS/SPDM already exist. For example, "end point" control allows the astronaut to command the motion of the end point of the manipulator rather than the individual joint angles. This mode of operation (so-called "flying the end point") could simplify control of the arms, which in turn would reduce the requirements for training.

If the time lag between input commands and system response does not cause errors (i.e., variations in signal travel time and signal processing time that are dependent on the communications path used in any specific instance) the SSRMS could be commanded from the ground to accomplish portions of a task. For example, a ground-based operator could control the transit of a component from one point on the ISS to another, leaving only the high-precision end task to the intravehicular activity (IVA) astronaut operating from inside the ISS. Routine maintenance tasks that do not require the resourcefulness of an onboard astronaut could also be transferred to ground operators.

NASA's current plans for operating the SSRMS/SPDM are conservative but adequate for the assembly phase of the ISS. However, improved operating modes would yield substantial benefits during the post Assembly Complete phase. Current plans do not include use of the SPDM to support EVAs or control of either the SPDM or the SSRMS from the ground.

Recommendation. The National Aeronautics and Space Administration and its international partners should develop a plan to incorporate improved control modes for the baseline robotic systems on the International Space Station (i.e., the space station remote manipulator system and the special purpose dexterous manipulator) that would simplify their operation and reduce astronaut training time (e.g., "flying the end point"). The plan should address cost and safety considerations as well as teleoperation by ground-based operators.

VISUAL INSPECTION AIDS

Additions to robotic systems on the ISS that could relieve astronaut EVA requirements would also yield substantial benefits after Assembly Complete. One of the most significant robotic capabilities currently under development is an enhanced visual inspection system. Current plans involve using the SSRMS for payload checkout before an SSRMS or

EVA task, for closeout photography, and for problem resolution. The SSRMS is a large, slow manipulator system that will not provide camera coverage of all parts of the ISS post Assembly Complete and cannot be operated without disturbing the microgravity environment.

The impact of having limited visual inspection capability has already been demonstrated. During STS-88, the first ISS assembly flight, repair of the undeployed antenna on the Zarya module was very difficult because of the lack of visual images. On this occasion, the EVA astronaut spent nearly an hour of EVA time trying to describe the nature of the problem to mission control. Nearly all of this time could have been saved if he had been able to provide mission control with a visual image (Ross, 1999). In this case, a camera on the EMU would have sufficed because the astronaut was already at the EVA work site. In other cases, when an astronaut is not at the EVA work site, an autonomous maneuverable camera could provide the critical visual inspection capability.

A visual inspection system called AERCam has been developed at the Johnson Space Center and has been flown on the Space Shuttle. AERCam is a small, free-flying, remotely controlled robotic platform that can carry a camera (or two cameras when stereoscopic images are warranted) and other sensors to any part of the ISS. AERCam can perform the following tasks:

- visual inspection
- pre-EVA reconnaissance
- closeout video documentation
- supplemental video coverage for other robotic operations
- positioning of cameras and lights for EVA crew
- nonvisual sensing (e.g., presence of ammonia, infrared camera, measurement of structural vibration)

The AERCam can be operated easily by an IVA astronaut and can be deployed without disturbing the microgravity environment of the ISS. AERCam has already proven its practicality. On the STS-87 mission, AERCam was operated in a teleoperation mode in close proximity to the Space Shuttle orbiter and within the operator's line of sight. Current procedures for inspecting the station exterior to assess damage cause major disruptions to the ISS microgravity environment. Although the AERCam system could satisfy the needs of the ISS, it is not currently on the manifest for the ISS.

Recommendation. Development and test of the AERCam system should be continued so that it can be included in the baseline International Space Station (ISS) equipment manifest for support of extravehicular activities.

ADVANCED ROBOTIC TECHNOLOGIES

In addition to improvements in visual inspection capabilities, improvements could be made in robotic systems to optimize the capabilities of the human-robot teams aboard the ISS and on the ground. Significant progress in robotics research promises to enhance the performance of robotic servicing systems through improved teleoperation modes and supervised-autonomous modes of operation for all of the planned or proposed robotic systems for the ISS.

Two research and development programs, the Ranger Project and the Robonaut Project being developed by NASA Johnson Space Center, are sufficiently well developed and have a high enough probability of yielding significant improvements to the operation of the ISS post Assembly Complete to warrant serious consideration. Both programs are focused on enhancing robotic servicer technologies.

The focus of the Ranger Project is on advanced telepresence control concepts. The goal is to develop techniques that will permit a remote human user (either IVA or on the ground) to operate the system easily to perform complex tasks. The current system, a mobile servicer with a main body and four arms, is controlled using stereo video displays, simulated graphics, dual three-axis hand controllers, and dual six-axis hand trackers. A robotic system with Ranger's capabilities could access objects in the tight confines of the assembled ISS structure that would not be accessible with the robotic systems now planned for the ISS (i.e., the SSRMS and SPDM). A Ranger vehicle would also be able to service the ISS without disturbing the microgravity environment.

The utility and value of the Ranger vehicle has already been demonstrated in tests at the Neutral Buoyancy Laboratory in which the vehicle functioned as an aid to astronauts performing ORU changeouts. The potential for incorporation of any of these capabilities into the ISS program is remote, however, until they have been demonstrated in flight. The Ranger vehicle is fully funded for a flight test demonstration (outside of the ISS program) but has not yet been manifested for a flight on the Shuttle.

A second robotic servicer program with great potential for the ISS is the Robonaut Project also being developed at the NASA Johnson Space Center. The Robonaut is an anthropomorphic robotic servicer comprised of two seven-degree-of-freedom manipulators attached to a torso with a stereo vision head. The robot is designed to match a suited EVA crew member in both size and dexterity. Because of its small size, the robot has a variety of mounting and mobility options. A unique aspect of the Robonaut is that it has a single end effector that can use the same tools and equipment interfaces as an EVA crew member. This end effector has four fingers and an opposing thumb and resembles a human hand.

The Robonaut concept is different from all other servicers that use multiple changeout tools (such as the Ranger). With the Robonaut servicer, EVA tasks currently designated "for EVA crew members only," including tasks within tight corridors and tasks that require simultaneous dual-arm operation, could be performed robotically. The Robonaut could be operated either by an IVA crew member or, potentially, from the ground.

Both the Ranger and the Robonaut technologies are available and could significantly improve the efficiency and safety of both EVA and IVA tasks. However, neither is currently planned to be incorporated or tested on the ISS.

Recommendation. The National Aeronautics and Space Administration should continue to explore advanced robotic technologies that have the potential to increase the efficiency of human-robot teams onboard the Internationaol Space Station. This should include space flight testing of the Ranger vehicle as a proof of concept.

Recommendation. The National Aeronautics and Space Administration should assess the potential improvements in extravehicular activities from the introduction of new robotic technology into human-robot systems. This assessment should include a comparison of the cost for development and implementation and the potential cost savings and risk reduction associated with the use of these systems.

EXTRAVEHICULAR ACTIVITY AND ROBOTICS

The current ISS robotic teleoperators require a significant investment of crew time for extensive training in operations that require great skill and attention to detail. The current ISS robotics are based on the successful history of the Space Shuttle remote manipulator system and do not represent a significant advancement in technology.

The ISS will provide a unique opportunity to establish synergistic activities by suited crew members and robotic systems. Highly mobile, reduced size and weight space suits and autonomous robotic systems with a high degree of dexterity are critical areas of research and development for which the ISS could serve as an engineering test bed. For example, a small HUT space suit, which is being considered for use on the ISS after Assembly Complete, could be used as a test bed for advanced technologies (i.e., automatic thermal control, advanced LSS, performance and physiological measures, actively controlled materials and structures, and biological technologies). In addition, two new prototype space suits have been delivered to NASA that could to be evaluated with robotic assistants (Hatfield et al., 1999).

NASA intends the ISS to be "an important test bed for solar system exploration" (Nicogossian, 1999). Therefore, the development of robotic technologies for servicing in space will be important for more than the ISS. Future HEDS (Human Exploration and Development of Space) initiatives, and solar system exploration missions, will also benefit from remotely operated robotic systems that can perform external inspections, servicing, maintenance, and repair. For unmanned missions, robotic servicing will be the only option.

Recommendation. The National Aeronautics and Space Administration should use the International Space Station (ISS) as a technology test bed for advanced extravehicular activity (EVA) systems, including robotic systems to support long-term ISS operations and future space missions. Rather than introducing only incremental changes, revolutionary approaches should be pursued to developing new materials, achieving greater mobility, and incorporating new technologies for both EVA suits and robotics systems in support of future exploration initiatives.

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5

Equipment Upgrades, Software, and Communications

Although the ISS has changed character many times, it retains many of the features of its predecessors, Space Station Alpha and Space Station Freedom, and includes design elements representative of 1970s and 1980s technology. By the time the ISS is operational in 2004, much of the technology and some of the hardware will be 20 to 30 years old. Considering the rapid growth in technology, upgrades to the operational ISS subsystems, hardware, and software could almost certainly increase the efficiency of the crews onboard and on the ground.

The committee suggests that NASA establish a metric for determining the cost effectiveness of improvements. The metric could be included in evaluations, along with other factors, such as safety and reliability. The following is an example of a simplified formula for evaluating cost effectiveness:

$$(t_s * c_s + t_g * c_g) / B_{t,}$$

where t_g and t_s represent savings in ground and space crew hours, respectively, and c_g and c_s represent the hourly cost of ground and space crews. B_t is the budget requirement for the improvement, adjusted for the time value of money for the interval between the investment and the midpoint of the expected savings. Improvements that have the highest value according to this metric should be considered first, and improvements with lower values should be considered only if they are required for safety or some other overriding reason. This type of metric, or an equivalent cost-effectiveness criterion, should be applied wherever possible.

COMMUNICATIONS

Communications with the ISS will be provided via the tracking and data relay satellite system (TDRSS) constellation of communications satellites. As currently configured, this system will provide for 42 Mbps downlink and 48 KBS uplink for science communications, with an availability of only 46-percent (i.e., the percentage of communication time, through TDRSS,when the s-band antennae are not being occluded by ISS structure) (Arend, 1998). Availability is constrained, at present, by the location of the antennae and the configuration of the surrounding elements of the ISS. NASA is considering upgrading the TDRSS to increase uplink bandwidth and is considering placing the ISS antennae on a boom to increase ISS-TDRSS mutual antennae visibility time. An upgrade to increase the downlink bandwidth to 150 Mbps at UF-5 is already in progress (Hall, 1999).

When upgraded to 150 Mbps, the downlink bandwidth should be adequate for sending telemetry and experimental data, but the uplink capability could be severely constrained because the signal availability of only 46-percent will affect both the downlink and the uplink communications. Significantly greater uplink bandwidth, with near continuous availability, will be necessary during the operational phase of the ISS program for the following reasons:

- If PIs control their experiments by teleoperation, they could attempt to control experiments while other communications are in progress, including ISS commands. Shared communications would be acceptable if bandwidth were adequate, but competing with other communications, under bandwidth constraint limitations, is not advisable.
- Mir experience with scientific experiments suggests that the ability to send drawings and pictures to the crew greatly increases their ability to respond to unanticipated experimental conditions or to make repairs.
- The ability to send real-time or near real-time video can significantly improve crew training, refresher training, and real-time repairs of flight hardware and experiments.

Recommendation. The National Aeronautics and Space Administration should make increasing the uplink bandwidth a high priority and should evaluate the importance of video communications.

Recommendation. The International Space Station antennae should be relocated in a configuration that allows continuous communication through the tracking and data relay satellite system.

PAYLOAD COMPUTING SUPPORT

The current approach to computer support for scientific experiments on the ISS is based on computing autonomy for each experiment (i.e., each experiment must provide its own unique computing capability). This arrangement is neither efficient nor sufficient. If each experiment provides its own dedicated computer, the variety in computing devices and software could significantly add to the complexity of the operation and increase the workload of the crew.

For experiments that do not require extensive or dedicated computing, NASA proposes providing a laptop interface via a 1553 bus to the payload computing module. The laptop would be selected from the commercial technology available at the time and would use commercial software. Experimenters would be able to send along a disk with the programs to be loaded for their experiments. Any computers (including those labeled as timers, controllers, or "smart sensors") that are not fully space qualified could malfunction due to space radiation thereby adding to the workload of the crew (Davidson, 1999). All computers will have to conform to standard interface specifications (i.e., ISS NSTS 21000-IDD-ISS).

Recommendation. The National Aeronautics and Space Administration should continue to refine the payload control/telemetry computing architecture in collaboration with the scientific community to ensure that the best technology is used and that computing devices are fully space qualified so as not to increase the workload of the crew.

HOUSEKEEPING COMPUTING-HARDWARE PLATFORMS

The ISS hardware architecture consists of a collection of federated processing modules on a 1553 bus. Each processing module is dedicated to a specific function. Communication between modules is managed through a synchronous message-passing protocol over the bus, which has been used extensively by the military and NASA avionics community (NASA CDH-TM Manual, 1999). The major advantage of this architecture is that it simplifies software integration. (Davidson, 1999)

U.S. Component

The hardware for the U.S. component, inherited from the Space Station Freedom program, uses the Intel 386 processor. The processors and circuit cards used to create the modules, which are at least a decade old, have enough power to perform the intended functions (and there is adequate reserve on the bus to add functions). Thus, they will not inherently add risk to the software. However, replacing hardware may be difficult.

NASA has instituted a policy of buying processing modules to repair failed units by replacing cards. Also, funding requirements for the Preplanned Product Improvement Program (P^3I) to replace the processors with more current 32-bit processors have been defined. Although this change will increase cost and add some risk, it would greatly improve the maintainability of the hardware.

Recommendation. The National Aeronautics and Space Administration should proceed with the Preplanned Product Improvement (P^3I) upgrade of the processor, even though this will require some changes in the software and will require that a new code generator be developed for the compiler.

Russian Component

The hardware for the Russian component consists of Intel 386-based modules provided by NASA and 32-bit SPARC processors provided by the European Space Agency. There are no plans to upgrade this hardware (Clubb, 1999).

SOFTWARE

The ISS housekeeping software architecture is dictated by the hardware architecture. As processing modules are dedicated to specific functions, the software is similarly allocated to the appropriate modules according to function. Software integration within a processing module is limited to the functions of that module, and software integration between modules is controlled by the synchronous message-passing protocol. The combination of functional decomposition and message-passing reduces, but does not eliminate, the complexity of integration (Panter, 1999).

U.S. Component

NASA has significant experience with the federated architecture, and mature processes are in place to manage the development and evolution of the software. These processes include detailed specifications by domain experts implemented by software experts. In addition, NASA has a mature and capable independent verification and validation procedure in place. Software changes can be tested on the ground and uploaded via communication links without waiting for a Space Shuttle mission. In the current plans, no major changes are anticipated in the systems supported and managed by the software (Panter, 1999). Software maintenance would be limited to fixing bugs and repairing or replacing failed or degraded system components.

Software testing for the ISS is necessarily dependent on simulations of the systems, such as a propulsion system to boost the station into higher orbit and computer hardware to test software integration. Although NASA has considerable experience with this approach, it carries significant risks. The committee recognizes that no alternative is available to the use of systems simulations, but reliance on hardware module simulations could be reduced by building a more complete ground system facility. The decision must be based on a present cost/future cost trade-off and safety assessment.

The committee is concerned that software development is currently behind schedule (Panter, 1999). Some of the schedule slippage can be attributed to the same system change flow-down that plagues most complex software. An initial build has been completed for all software to support the ISS through Flight 7A and software maintenance after Assembly Complete appears to be manageable.

Although P^3I funding requirements have been defined for upgrading the Ada Compiler to full compliance with language features in fiscal year 2000, P^3I funds have not yet been allocated for the development of a code generator and run-time operating system for the 32-bit replacement processor and subsequent software modifications. Although a strongly typed high-level language such as Ada will reduce the effect of conversion from a 16-bit processor to a 32-bit processor, the change will undoubtedly have some impact on cost and schedule.

Recommendation. The National Aeronautics and Space Administration should review its Preplanned Product Improvement (P^3I) plans to ensure that funds will be available for the development of a code generator and run-time operating system for the new processor and for subsequent software changes.

Russian Component

The Russian software is being developed under conditions drastically different from U.S. software development (Clubb, 1999). The Russians are using two different types of processors and two different run-time systems, one based on the European Space Agency's operating system developed in Ada language for the SPARC processor using the C language for applications, the other based on the Ada language run-time for the 386-based processing modules. Domain experts, who usually operate with much looser specifications, are writing the code. Domain experts also typically build more complex, less structured software with embedded assumptions that complicate changes.

Although the Russians have very capable programmers, they are not experienced with large complex systems, the languages and compilers being used, and high-level integration with U.S. software for important functions, such as guidance and navigation, commanding, telemetry, and support of ISS modes after Flight 5A.

In the later stages of assembly and after Assembly Complete, maintenance of the Russian software could pose significant risks, which could be complicated by the dynamics of the Russian economy. If the commercial software industry continues to develop rapidly in Russia, the people who write the code may move on to other jobs and may not be available to maintain ISS software.

Recommendation. The National Aeronautics and Space Administration should develop a risk mitigation strategy for the maintenance of Russian-developed software.

TELECOMMUNICATIONS SECURITY

The safety of the ISS and its crew and the success of the experiments will depend, in part, on secure communications. Software upgrades must be uploaded, and commands issued to control a variety of station-keeping activities. The telecommunications system for the ISS is necessarily complex because of the number of international participants who will have to communicate with their respective segments. The system is further complicated by the possibility that some in the scientific community may manage their experiments through teleoperations and by the needs of some research organizations and commercial enterprises to protect proprietary information.

The safety of the ISS and crew, and the integrity of the experiments, will require a sophisticated security scheme to protect communications and information systems. Security is especially important in the current environment in which networks and systems are under constant attack by amateur and professional intruders. The ISS will be a highly visible target for people who would consider "cracking" its security wall the ultimate challenge.

NASA has a well conceived security architecture based on experience with previous systems, and the agency undergoes an independent security evaluation every year. The security architecture has multiple levels of protection, including encryption. The initial encryption is based on the DES algorithm, which is known to have been broken. The P^3I plan is to upgrade the algorithm to the triple-DES algorithm, which is a more robust 128-bit system. Although that would be a significant improvement, recent developments suggest that even greater security (i.e., 256-bit or greater) encryption will be necessary. Despite NASA's careful attention to security, other potential vulnerabilities must still be remedied.

Recommendation. The National Aeronautics and Space Administration should accelerate the upgrading of the encryption to triple-DES, continue to plan aggressively for further upgrades as the technology develops, and should perform a thorough analysis of the system to identify vulnerabilities.

SUMMARY

Despite conscientious planning by the ISS Program Office and the Engineering Directorate at the NASA Johnson Space Center to identify systems and procedures that need upgrading to support NASA's vision of a world-class research facility on orbit, many upgrades and improvements are being deferred. The committee believes that the fundamental improvements cited in this report can and should be introduced into the ISS as soon as possible and that special management oversight is warranted in the following critical areas:

- the P^3I program to ensure that P^3I continues to be a responsible advocate for important ISS upgrades and that it is adequately funded
- changes to ISS provisioning and planning techniques to ensure that proper consideration is given to program parameters that affect the acquisition of spare parts and logistics planning for the ISS operational phase
- the implementation of communications system upgrades to improve critical uplink communications for the mutual benefit of crew members, PIs, and international partners
- the continued development of capable robotic aids, especially systems that will facilitate EVAs and make certain EVA tasks easier, or even unnecessary
- the reassessment of traditional detailed mission planning and control procedures with the goal of significantly reducing the numbers of ground controllers supporting the long-term operations by allowing long-term crew members aboard the ISS, who have unique experience with the ISS equipment and the scientific experiments, to participate in planning day-to-day activities
- the reassessment of traditional mission control procedures and staffing to take advantage of improved communications technologies that will enable access to key personnel from remote locations, thereby reducing the requirement that a large contingent of mission control personnel be continually on site in the mission control center.

Recommendation. The National Aeronautics and Space Administration should designate a senior member of the International Space Station (ISS) staff to assemble, review, and approve budgets and implementation plans for post Assembly Complete, to facilitate improvements in ISS systems, and ISS operations, and to maintain a high degree of management visibility for this important activity.

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6

End-of-Life Disposal

At some point in the future, the ISS will have to be decommissioned, deorbited, and returned to Earth. The return of the ISS will require stringent safety standards to minimize third-party damage and avoid casualties. NASA has performed, and must be commended for, its detailed analyses of the requirements for and methods of end-of-life disposal of the ISS in a manner consistent with NASA's stated safety requirements (i.e., less than a 1 in 10,000 chance of a casualty from reentry operations).

NASA has performed a number of analyses related to ISS end-of-life disposal, including an analysis performed for the International Space Station Alpha (ISSA), a space station configuration that preceded the current ISS design (NASA, 1995). The analysis consisted of a risk assessment, a controlled deorbit analysis, a debris dispersion analysis, and a disposal area assessment. Additional analyses were also performed based on the use of a U.S. propulsion module (Thorn, 1999).

The disposal risk assessments concluded that the risk to human life from an uncontrolled ISS reentry would be unacceptable, ranging from a 0.024 to a 0.077 chance of a single casualty (i.e., 2 in 100 to 8 in 100). On the assumption that a failed deorbit mission would result in an uncontrolled reentry, with about a 0.05 chance of a casualty, then even a 1-percent chance of a failure exceeds NASA's stated safety objective. According to NASA's safety guidelines, the casualty risk must be limited to a 0.0001 chance of a single casualty (i.e., 1 in 10,000). The risk assessment, therefore, included other alternatives, such as: boosting the ISS to a much higher orbit to prolong its on-orbit lifetime; disassembling and returning ISS components to Earth via the Space Shuttle; and controlling and targeting reentry to a safe location in the oceans.

In one analysis conducted for the ISSA, an end-of-life deorbit maneuver could begin from a circular orbit after the two Soyuz vehicles had been separated from the station. After separation of the Soyuz vehicles, the Progress vehicle(s) and the service module, both fully loaded with propellant at the beginning of the maneuver, would be used for the deorbit burn (Thorn, 1999).

A more recent study was done with end-of-life disposal performed by a U.S. propulsion module. This study established deorbiting criteria based on the U.S. propulsion module directing the reentry to a remote ocean area to ensure that the dispersed surviving debris "footprint" would not fall within 370 km (200 nmi) of any land mass. The ISS deorbit trajectory would be designed so that natural orbit decay would lower the orbit to the point where excessive attitude control propellant would begin to be needed (i.e., about 241 to 185 km [130 to 100 nmi]). Solar arrays would be positioned to minimize aerodynamic torque. At 222 km (120 nmi) altitude, the U.S. propulsion module would lower perigee (the lowest point in the orbit) to an altitude of approximately 140 km (75 nmi) with orbit adjustments made over several orbits because of the long burn times needed to achieve the required change in orbital velocity (Δv). A final deorbit burn would then lower perigee from 140 km to 83 km (75 to 45 nmi) altitude reaching at least a 16.8 m/s (55 fps) Δv in a period of 35 minutes. Solar arrays would collapse at about 130 km (70 nmi) altitude as the ISS begins its atmospheric reentry profile.

As a result of the reentry and subsequent breakup of the ISS, surviving debris would be scattered over the surface of the Earth. About 80-percent of the debris would vaporize in the atmosphere. The debris impact footprint is affected by many factors, including deorbit maneuver accuracy, range of debris ballistic coefficients, breakup altitude, breakup Δv, atmospheric density, winds, and debris aerodynamic lift. Assuming a successful reentry mission, NASA analyses have concluded that the ISS dispersed debris footprint could be as large as an ellipse measuring 300 km by 5,370 km (162 nmi by 2,900 nmi). Therefore, ocean disposal will be necessary. The largest disposal region, in the eastern Pacific Ocean, would allow the initiation of deorbit maneuvers on either of two consecutive orbital passes over the area.

NASA has concluded that the U.S. propulsion module, as presently designed, will not be able to meet the performance requirements of the ISS end-of-life deorbiting mission (Thorn, 1998). To achieve the deorbiting mission requirements, the U.S. propulsion module would have to burn more than 142 kg (5,000 lbs) of propellant, developing 3,556 Newtons (800 lbs) of thrust for a duration of 35 minutes to complete the final deorbiting burn.

NASA concluded that boosting the ISS to a higher orbit is not an option because of insufficient propellant and because the orbit would gradually decay to a lower orbit, and the ISS would ultimately deorbit in an uncontrolled reentry. Another alternative, disassembly of the ISS, was considered too expensive (the ISS is not designed for disassembly). The committee concurs with NASA's conclusion that the only viable solution for ISS end-of-life disposal is controlled deorbiting of the ISS.

Based on these assessments, a controlled ISS reentry to a remote ocean area would be the safest disposal option. Therefore, ISS end-of-life disposal requirements will have to be incorporated into the U.S. propulsion module design requirements. NASA believes that a deorbiting mission must have at least a 99-percent reliability. The committee believes that even this reliability level would not meet NASA's safety goal of a less than a 1 in 10,000 chance of a casualty.

Recommendation. End-of-life disposal should be accomplished by a controlled deorbiting of the International Space Station. Sufficient onboard propulsion must be provided for this operation. The National Aeronautics and Space Administration should consider upgrading the U.S. propulsion module to provide the required deorbiting capability.

Recommendation. Because of the potential hazards associated with the reentry of relatively large objects, the safety requirement for International Space Station reentry should be more stringent than the requirement for other National Aeronautics and Space Administration operations (i.e., the chance of casualties should be much less than 1 in 10,000).

NASA's calculations of the probability of success of the final deorbit burn do not make enough allowances for the fact that these operations will take place in the very stressful environment of reentry, which will include the heating, vibration, and collapse of subsystems. Therefore, NASA cannot ensure that the U.S. propulsion module will have a greater than 99-percent probability of success. In fact, the committee believes that the reliability of the U.S. propulsion module will have to exceed 99-percent to achieve NASA's stated safety objectives.

Recommendation. The National Aeronautics and Space Administration should undertake a thorough analysis of International Space Station reentry operations, including ranges of uncertainty associated with the multiple variables of reentry operations. The analysis could take the form of a Monte Carlo simulation of reentry operations and projected impact areas to characterize the hypothetical potential for property damage or casualties. The analysis should include the sequence of operations, possible failures, and consequences of failures, from the initiation of reentry operations to final impact. Uncertainty variables should include, but should not be limited to, reliability characteristics, duration of burn, atmospheric density, ballistic coefficients of fragments, population densities, and the characterization of acceptable impact areas.

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Appendixes

Appendix A

Statement of Task

The study will assess the potential effect of long-term operational engineering issues on the budget and capabilities of the International Space Station (ISS) and, where appropriate, recommend procedures and hardware upgrades to mitigate their impact. The study will focus on the following issues:

1. Long-term ISS maintenance requirements.

2. Extravehicular activity (EVA) requirements to support ISS operations and maintenance (in light of experience with the Mir space station).

3. The use of an international fleet of launch vehicles to support the ISS.

4. The need for—and capability to—upgrade and replace ISS equipment and components after the station's assembly is complete. This includes the need to replace laboratory equipment as it becomes obsolete.

5. Decommissioning and disassembly of the station at the end of its useful life.

Appendix B

Biographical Sketches of Committee Members

Thomas Kelly, chair, is retired president of Grumman Corporation's Space Station Integration Division. Mr. Kelly worked for Grumman for 40 years, during which time he directed Grumman's engineering work on the Apollo Lunar Module and worked on the Space Shuttle and Space Station Freedom programs. He is a member of the National Academy of Engineering and a fellow of the American Astronomical Society, the American Society of Mechanical Engineers, and the American Institute of Aeronautics and Astronautics. Mr. Kelly was a member of the National Research Council Committee on the Use of the Space Station for Engineering Research and Technology Development and the Committee on Space Station Meteoroid/Debris Risk Management. He has an M.S. in industrial management from the Massachusetts Institute of Technology, an M.S. in mechanical engineering from Columbia University, and a B.S. in mechanical engineering from Cornell University.

John Blaha is the assistant vice president of applied research at United Services Automobile Association. He served in the U.S. Air Force for 15 years (completing 361 combat missions) and as an astronaut for the National Aeronautics and Space Administration (NASA) for 17 years. Mr. Blaha logged five trips into space as a commander, pilot, and mission specialist on Space Shuttle flights and as a cosmonaut researcher during a four-month stay on the Mir space station. He has chaired the NASA Space Flight Safety Panel, led the design, development, and integration of the orbiter Head Up Display System, and led the development of contingency abort procedures for the Space Shuttle. Mr. Blaha has received numerous awards, including the Order of Friendship Medal from Russian President Boris Yeltsin, two NASA Distinguished Service Medals, and two Air Force Distinguished Flying Crosses. He received a B.S. from the U.S. Air Force Academy and an M.S. from Purdue University.

Bert Bulkin is director of scientific space programs (emeritus) at Lockheed Missiles and Space Company. Mr. Bulkin was the program manager for the Hubble Space Telescope and was also in charge of its maintenance, refurbishment, logistics, and servicing. Previously, he was the director of advanced systems development at ITT's Electro-Optical Division. He has a B.S. in aeronautical engineering from the University of California, Los Angeles (UCLA), and completed postgraduate work at UCLA and the University of Santa Clara.

John T. Cox is a project manager/consultant at CSC Healthcare. Previously, he served as operations director, deputy manager, and acting program manager of NASA's Space Station Freedom Program. Dr. Cox trained flight crews and flight controllers for the Apollo and Skylab programs and was flight director for many of the Space Shuttle's "first of a kind" flights. He also developed organizational changes to bring a business attitude to NASA Headquarters. He has worked with the Nuclear Regulatory Commission and the Electric Power Institute and served on the NRC Committee on the Use of the International Space Station for Engineering Research and Technology Development. He has a Ph.D. from the University of Houston.

Larry E. Druffel is the president of SCRA, a public nonprofit organization engaged in applying advanced technology to increase industrial competitiveness. Previously, he was director of the Software Engineering Institute and vice president for business development at Rational Software. Earlier in his career, Dr. Druffel was on the faculty at the U.S. Air Force Academy. He later managed research programs in advanced software technology at the Defense Advanced Research Projects Agency, was founding director of the Ada Joint Program Office, director of computer systems and software (Research and Advanced Technology), Office of the Secretary of Defense. He is a fellow of the Institute of Electrical and Electronic Engineers and the Association of Computing Machinery. Dr. Druffel received his Ph.D. in computer science from Vanderbilt University.

Joel Greenberg, the president of Princeton Synergetics, Inc., has more than 40 years of experience in financial analysis, market forecasting, economic analysis, systems analysis, operations research, policy analysis, and commercialization. Mr. Greenberg has been responsible for a broad range of financial, benefit/cost, economic, and policy studies related to space transportation, space insurance, space system life cycle cost and availability, and commercial development of space. He has been a major contributor to the field of economic, financial, and risk analysis of space systems and operations and business situations influenced by government policies and programs. Mr. Greenberg is a fellow of the American Institute of Aeronautics and Astronautics and an elected member of the International Academy of Astronautics. He has an M.E.E. degree from Syracuse University.

Herbert Hecht is founder and chairman of the board of SoHaR, Inc. He has worked extensively on space systems reliability and is the author of the *Handbook of Flight Critical Systems* (U.S. Air Force Aeronautical Systems Division, January 1985) and a technical report on spacecraft electronics reliability prediction based on analysis of more than 2,500 spacecraft failures. Dr. Hecht has written chapters on reliability in several textbooks, including *Space Mission Analysis and Design* (Kluwer Academic Publishers, 1997) and *Reducing Space Mission Cost* (Kluwer Academic Publishers, 1996). Prior to founding SoHaR, Dr. Hecht worked for 15 years at the Aerospace Corporation and 14 years at the Sperry Rand Corporation. He received his Ph.D. from the University of California, Los Angeles.

Andrew J. Hoffman is president of East Windsor Associates, a technical and management consulting firm. Previously, he was vice president of space and sea systems and executive vice president of Hamilton Standard, where he was the program manager for the Lunar Module life support system, Skylab crew equipment, and the Space Shuttle life support system. His areas of technical expertise include extravehicular mobility units, space vehicle life support, thermal control, and system analysis. Mr. Hoffman served on the NRC Committee on Advanced Technology for Human Support in Space. He completed his M.S. in management science at the Hartford Graduate Center.

Jack Kerrebrock is a professor of aeronautics and astronautics at the Massachusetts Institute of Technology (MIT). He joined the faculty of MIT in 1960 where he remained as professor, department head, and associate dean (except for two years as associate administrator for aeronautics and space technology at NASA). Dr. Kerrebrock is a member of the National Academy of Engineering and chaired the NRC Committee on the Space Station. He has also served as member and chair of numerous other NRC and NASA committees. Dr. Kerrebrock received his Ph.D. from the California Institute of Technology.

Dava Newman is an associate professor of aeronautics and astronautics at the Massachusetts Institute of Technology (MIT). Her multidisciplinary research in extravehicular activity systems and the dynamics and motor control of astronaut performance combines aerospace bioengineering, control and dynamics, human interface technology, and systems analysis and design; the work is being carried out through flight experiments, ground-based simulations, and mathematical and computer modeling. Dr. Newman served on the NRC Committee on Advanced Technology for Human Support in Space and is currently a member of the Aeronautics and Space Engineering Board. She received a B.S. in aerospace engineering from the University of Notre Dame and an M.S. and Ph.D. in aerospace biomedical engineering from MIT.

Stephen Rock is an associate professor of aeronautics and astronautics at Stanford University. Previously, he was manager of controls for Systems Control Technology, California, and development engineer at Hewlett Packard. His main areas of research are the application of advanced control techniques for robotics and development and the application of innovative control approaches for vehicle applications. Dr. Rock served on the NRC Committee on the Use of the International Space Station for Engineering Research and Technology Development. He received his Ph.D. in applied mechanics from Stanford University.

Appendix C

Phase 1 Mir Program

INTRODUCTION

Phase 1 of the International Space Station (ISS) was a National Aeronautics and Space Administration (NASA) program encompassing 11 Space Shuttle flights and one Soyuz flight over a four-year period from February 1994 to June 1998. During Phase 1, seven U. S. astronauts spent 31 months aboard Mir working with their cosmonaut crew mates supporting Mir operations and conducting scientific experiments. Existing assets, primarily the Space Shuttle, the Russian Soyuz, and the Russian space station Mir, were used.

In a review of the lessons learned from the Phase 1 Mir program, the committee found some similarities and many differences in the approaches taken by the Russians for the Mir and by NASA for the ISS. One of the primary shortcomings on Mir was the limited availability of communications with the ground. The Mir experience reaffirms the committee's opinion that the ISS will require 100 percent communications availability through the tracking and data relay satellite system.

The two major sources of information pertaining to the Phase 1 Mir program were the NASA's lessons-learned documentation (NASA, 1998) and responses to questions from the committee about the Phase 1 Mir experience in the areas of maintenance and repair, extravehicular activity, station operations, and crew timelines. The questions and answers are reprinted in this appendix. The answers were prepared by the NASA Phase 1 ground support personnel with management review and comments.

QUESTIONS ABOUT THE PHASE I MIR EXPERIENCE[1]

Introductory Remark

We [NASA] do not have direct information to answer these questions in a rigorous sense. The following answers are based on primarily our observations during the Phase 1 program, by both crewmembers and ground personnel. Efforts continue to increase our detailed knowledge of the history of systems that will be flown on ISS.

Maintenance and Repair

1. What type MIR equipment has the greatest maintenance requirement (ground, on-orbit)?

Maintenance takes several forms (preventive and corrective) and can have different levels of impact to station operations. For example, the Elektron oxygen generators are "fussy" in the sense that they often require attention from the crew to purge air bubbles from the water supply line or to respond to pressure anomalies that may temporarily take the unit offline. These are due to the fact that the Elektron generates hydrogen as well as oxygen and safety systems shut the unit down as the conservative response to preclude accumulation of hydrogen in the vehicle. In addition, the Elektron supply and overboard vent lines must be cleaned periodically. On one occasion, cleaning the vent required EVA operations on two different EVAs, but it was possible to schedule the tasks with other EVA tasks to reduce the time impact. The Elektron system to be flown on ISS will be similar to the Mir units.

Another system that required a significant amount of maintenance is the gyrodine momentum storage system. The externally mounted system on Kvant 2 exhibited a rapid failure rate and did not perform as well as was hoped, and therefore was not maintained. Instead, internally mounted gyrodines were added in flight. These have functioned satisfactorily and comprise the system which is currently operating. The failure rate of the gyrodines has been significant, but many of those failures were induced by other factors. For example, the units use a magnetic suspension system to reduce wear and drag internally and a normal

[1] The questions and answers have been printed verbatim and have not been edited.

shutdown maintains the suspension until the rotor has spun down. However, on quite a few occasions during the latter part of the Phase 1 Program, unexpected losses of electrical power resulted in rapid stopping of the units, causing with premature termination of the magnetic suspension. This resulted in predictable damage to some parts of the units. Some spares for these parts were kept on board for this scenario, and the crew was very proficient in performing the task. However, the spares were eventually depleted.

The Solid Fuel Oxygen Generator, or SFOG is another system with maintenance requirements characteristic of the Russian design approach.. This is a very simple unit with only two moving parts: an electric fan and a spring-powered striker assembly used to trigger the initiator pellet for the SFOG cartridge. While we are unaware of any failures of the fan, it is a common type that is widely used on the Mir and several spares are usually on board. The striker assembly is subject to wear with high use, which can result in the need to make several attempts to initiate the cartridge reaction. The striker assembly is easily and regularly changed out.

The Mir's roll-axis thrusters are located on the end of the Sofora truss boom in a self-contained unit. This unit has been replaced twice over the life of the Mir when its propellant was exhausted. In neither case was a failure of the hardware involved and, despite U.S. reservations concerning the changeout task's feasibility, both changeouts were completed without incident. However, the task is lengthy and complex, involving multiple EVA's (three or more) and the use of a special Progress vehicle to carry and position the replacement propellant unit. Another task that required a great deal of ground attention and crew time was the identification and repair of cooling system leaks. For various reasons the Mir had a relatively high incidence of condensate present on the walls of some modules. This, combined with an unfortunate choice of metals for grounding straps, led to dissimilar metals corrosion that caused perforation of the coolant loop tubing in a number of places. Once the problem was identified, locating the sources of the leaks rapidly escalated to being the major crew task for several months during the Spring of 1997. Concerns regarding habitability and exercise also resulted from of the leakage of the ethylene glycol coolant into the cabin atmosphere. There was no direct health threat due to this leakage, but it was a major irritant to the crew and limited exercise opportunities. The inability to exercise can become a constraint to keeping the crew on board, but the problem was resolved without evacuation. Design improvements have been made to ISS to better control the humidity level and prevent dissimilar corrosion should it occur. As a third corrective action, the coolant in use on ISS is a non-toxic, non-irritating material.

2. What type of Mir equipment has the highest replacement rate?

Exact data not available, but the following items have been observed. They are listed in no particular order:

- filters and other consumables
- batteries
- gyrodines
- avionics boxes
- SFOG strikers

3. How have actual failure rates of equipment on Mir compared with the earlier projections?

We do not have sufficient data to be quantitative on this, but the following observation is offered. Mir was designed to be maintained, operated, and have some research performed by a crew of two, with the addition of a third crewmember to be dedicated to research. This objective has basically been met, although in recent years very long hours have been required on many occasions. The condition of the station has led to the need for higher than usual effort to restore normal functionality to on-board systems. This activity reached a peak in 1997, and a major push by the crew resulted in the maintenance demands and overall station reliability being much improved from late 97 at least through mid 98 when the last U.S. crew departed the station. We have little data for the period after the U.S. crew left Mir.

4. What types of failures were encountered (design flaws, environmental, usage, random)?

All of the above, as would be expected with a program of this length.

5. What was the planned Mir sparing philosophy and how did it compare with actual?

The planned sparing philosophy was to "replace as specified in design documents," which means replacing each item at the end of its predicted reliable lifetime. In reality, as experience was accumulated and pressure on spares availability grew, the philosophy changed to operate non-critical hardware until failure. This is the norm in the U.S. aerospace industry and is the plan for the U.S. segment of ISS (with careful definition of the term "failure") as it makes an enormous difference in the spares population required and resulting cost. The Russian program is particularly well suited to this approach since in addition to having highly maintainable hardware on orbit, the Progress cargo vehicle manifest can be changed at a relatively late date to respond to late-breaking requirements. In addition, the Russian philosophy is to retain critical parts on orbit, even when they have shown some degradation, rather than to discard them, since a deorbited Progress is not recoverable and failed hardware returned in it is lost. Therefore, when a computer has a partial failure, for example, it is replaced as soon as possible with a new unit but the failed unit is retained against its possible use as a temporary spare. Also, the predicted failure rates of some items such as fans was overstated to the point where an excessive number was kept on board. This was eventually corrected, but since the process for maintaining on-board inventory was evolving, it took some time to determine.

6. If you were starting over with Mir, what changes would you make to reduce maintenance cost and time?

From a maintenance and logistics perspective, NASA does not have sufficient knowledge to say much at this time.

Some improvement in demand for consumables and other evolutionary items would be good, and experience has reinforced the importance of tracking the maintenance and logistics demand rather than letting it get behind.

Positive examples from the Mir include the high degree of on-orbit maintainability of the hardware, permitting the resupply of smaller components rather than larger units, the large proportion of internal hardware to be maintained rather than extensive EVA requirements, and a highly responsive logistics resupply vehicle (Progress) capable of carrying replacement items, both IVA and EVA, on relatively short notice. Another key element is an emphasis on skills-based training for the crew so that they can accomplish any maintenance task that arises while the crew is on-orbit.

Negative examples from Mir include the necessity to perform certain types of repair operations, such as cutting of materials, on-orbit. The increase in atmospheric particulates (such as dust) which resulted from some of these activities is undesirable. Likewise, the procedures for repairing the coolant leaks were ineffective in preventing further leakage of the coolant into the atmosphere. Finally, the lack of a descent vehicle capability for returning failed hardware drives replacement unit costs and prevents failure analysis for design improvements.

7. What has proven to be the most important characteristic of the MIR internal systems, (robustness, reliability, redundancy)?

All three apply. It is difficult to determine what could be named the single most important characteristic of a Mir system. Very many of Mir's internal systems were brand new, and this may have been of utmost importance. Mir software was developed and modified on an "as-needed" basis, during the entire life span of the station. The same philosophy (change with changing environment, think on your feet, be flexible, be adaptable and creative) was applied to all internal systems of Mir and became the core philosophy enabling the station to fly, albeit with some difficulties, almost twice as long than was originally predicted.

Extravehicular Activity

1. What part of the MIR program has the highest EVA requirement?

Of over 350 total Mir EVA hours, three categories of external work are apparent :

Assembly - 52%
Science - 24%
Maintenance/Contingencies - 25%

2. How many "preplanned EVA" hours does the MIR program plan annually?

From 1987–1998, an overall average of about 20 hours of EVA assembly and science were planned each year. In more recent years (1995–1998), the rate of Mir EVA increased to seven to ten EVAs per year (39–55 hours per year).

3. How many "unplanned EVA hours" have occurred each year, for the first three years, and for the most recent three years, of MIR operation?

Over the life of Mir, 1/4 of the EVA work was "unplanned" as noted in the answer to question one. In the first three years, (1986–1989), only one EVA of 3.5 hour duration was unplanned (to free debris preventing docking between Kvant1 and Mir modules). In the last three years (1997–1998), a total of 30 hours of unplanned EVA was expended (1 hour for antenna anomalies in 1996, 24 hours for Spektr repairs in 1997–1998, 5 hours in 1997–1998 for the Kvant2 hatch).

4. What have been the actual EVA hours each year since the start of the MIR operational phase?

Based on available data, the approximate annual Mir EVA hours are:

1986 - 0
1987 - 9
1988 - 19.5
1989 - 0
1990 - 32
1991 - 53
1992 - 24.5
1993 - 24
1994 - 11
1995 - 39
1996 - 46
1997 - 77
1998 - 36
1999 - 0

5. How do the estimates of EVA time compare with actual time spent EVA?

From first hand experience with the Mir-23 and Mir-24 EVAs, the typical Mir EVA was planned for a 5 hour 30 minute duration. The actual duration often increased by about 10% or 30 minutes.

6. How much time did you put in the on-orbit timeline for a crewmember's training and preparation to perform an EVA?

Based on detailed study and experience with Mir-23 and Mir-24, pre-EVA crew time (including on-orbit training) ranged from 9–54 hours, but was normally about 22 hours. Response to unplanned contingencies requires considerably more preparation than those tasks trained and executed per pre-flight plans. The second or third EVA in a related series requires much less overhead than the first.

7. What is the failure rate for the MIR space suit assembly? Has it improved over time?

Mir is normally provisioned with three Orlan suits and numerous spare parts. Of the 76 Mir EVA sorties, two ended early due to O_2 regulator and cooling failures and three were degraded but not stopped by cooling and humidity removal problems. Only one of the EVAs since 1997 has required the use of the spare suit (fan problem). The Orlan suit has evolved since Russia's manned lunar mission era with design issues being addressed along the way. The same Orlan M design that has been used for Mir EVAs since 1997 will also be used on ISS. Though a specific failure rate is difficult to compute with the limited data in hand, no show-stopping hardware failures have occurred in recent years.

8. What suit/life support system enhancements have been required?

Russian initiated improvements from the Orlan DMA to the Orlan M include :

- Increased suit service life from 10 to 12 sorties
- More volume in upper torso for larger crew
- Better and more capable humidity removal
- More mobility in lower legs and arms via new bearings
- New overheard window/visor and brighter helmet lights to improve visibility
- Easier on-orbit arm/leg resizing
- Elimination of low pressure mode of suit pressure regulator

Joint agreements have resulted in the following:

- Option for U.S. safety tether attachment
- Option for U.S. rigidizable equipment/body restraint tether
- Common foot restraint platform to hold both EMU and Orlan boots
- Option for U.S. crew preference items (moleskin, underwear, comfort gloves)
- Future attachment of Orlan specific self rescue jet pack (SAFER)

9. If you had it to do over, what changes would you make to the EVA system (suit/LSS)?

From a U.S. perspective, NASA would:

- Enhance suit size range to fit more large and small crewmembers. Improve arm mobility and glove dexterity. Correct glove and boot thermal comfort issues. Make the umbilical easier to mate/demate when pressurized. Never design an EVA hatch to open outward.
- Implement a larger GCTC water tank for more integrated mockup layout. Improve mockup fidelity.
- Increase the limited number of Russian EVA ground personnel. Get one to two of them to reside in Houston on a permanent/rotating basis. Improved access to overseas facilities, hardware, procedures, and drawings.

10. What is the estimated cost of an EVA hour in the Mir program?

NASA does not have sufficient data to provide an estimate.

11. What were some of the cosmonauts' tasks that required EVA?

- Deployment and retrieval of numerous small and mid-sized science experiments
- Construction of truss experiments
- Transport, installation, and deployment of solar arrays and attitude control thruster packages
- Routing, restraint, and connection of cables
- Backup manual release of a jammed antenna and solar array
- Transport of crew and large objects via Strela cargo crane
- External inspections after MMOD events
- Still and video camera photography

- Spektr module repairs (power connections, leak detection, solar array reinforcement)

12. How was the prediction for EVA aboard the ISS made? Based on what criteria?

The same Russian engineers who supported Mir EVA also are responsible for ISS EVA planning. Until water tank testing is performed, they base their estimates on an experienced assessment of flight hardware drawings and direct similarity to past on-orbit Mir work.

Assembly is the primary driver for Russian ISS EVA. Science is piggybacked onto existing EVA time and therefore has not yet had an impact to total ISS EVA demand. Maintenance is estimated at two to three days per year. Resources for up to two days of unplanned Russian EVA are reserved on every increment.

NASA reviews and approves all Russian EVA demand via the EVA Project Office's Multilateral EVA Control Board (MECB). This forum manages the integrated schedule, content, sequencing, etc., of both U.S. and Russian EVA to ensure safety, success and efficiency.

Station Operations

1. What areas have been most critical to the efficiency of the station?

From our observations, the Motion Control System, Electrical Power System, and Oxygen generation systems have been the most critical and impacting to station operations.

2. How many mission support people are required on the ground to tend MIR (average day)?

Approximately 20 people constitute each Mir flight control team 24-hour shift. This number does not include personnel associated with MCC-M facility operation, ground station network operations, or Mir systems engineers providing real-time consultation with the flight control team. Additional flight control and MCC-M personnel are also present to provide planning for future 24 hour shifts two to four days in advance of execution.

3. What are communications bandwidths (uplinks and downlinks) and how much communications time is averaged per day?

Voice Communications: Two 30 kHz bandwidth VHF FM voice channels are available for crew-to-ground communications via ground stations. With the combination of NASA and Russian VHF ground stations, a minimum of ten minutes of VHF FM voice communication is typically available of each daily orbit. Communications sessions average 20–25 minutes in length during the ten orbits which constitute the crew work day.

Packet Data Communications: One of the VHF FM voice channels can be used to send 9.6 kbaud "packet" data, a type of e-mail transmission commonly used in the amateur radio community. This is typically done during at least three communication sessions per day.

Telemetry Data: Two 256 kbps telemetry streams are used to provide systems data to MCC-M via Russian ground stations. The Russian telemetry ground stations are available for 9 of the 16 daily orbits and are used whether the crew is awake or not. Telemetry communications sessions average 20–30 minutes in length. Telemetry is not available via NASA ground stations.

Command Uplink: One 64 Kbps UHF command uplink is used for Mir station commanding from Russian ground stations only. Command capability is not available via the NASA ground stations.

Satellite Communications: Voice, video, and limited telemetry data was also available via the Altair relay satellites. However, this system experienced frequent operational problems with the on-board Mir satellite communications equipment, the Altair satellites and the Altair satellites' ground stations. Consequently this system was used on a limited basis (three to four times per week maximum depending on system availability) and generally done when out-of-range of the Russian ground stations. Communications sessions of one Mbps voice and television or one Mbps telemetry and voice could be provided for up to 45 minutes using Altair. Limited command capability was also available at 64 kbps. This system has not been used since March 1999 due to the failure of the last remaining relay satellite.

Crew Timelines

1. How valuable is the time spent performing on-orbit handover?

This was invaluable for both Russian and NASA crew members.

2. What percentage of crew time did you allocate for on-orbit handover for those occasions when 2 Soyuz were docked at Mir?

NASA operations were not impacted by the presence of two Soyuz crews. Handover remained the highest priority and largest time consumer for the Russian Commanders and Flight Engineers of both Soyuz crews. Handover activities constituted at least 50% of crew time during the handover period.

3. How much time was in the crew timeline each day to perform exercise?

Three hours per day is the Russian medical requirement. This is normally broken up into two 90 minute exercise sessions.

4. How much time is required for relaxation periods each week for a long duration space flight?

Weekends and all Russian holidays are considered off-duty days for the crew. The Mir crew is normally scheduled for an 0800–2300 Moscow time work day. Morning wakeup, breakfast, lunch and dinner time in addition to at an hour of personal time at the end of each day are scheduled and considered non-work periods.

5. How much time is required each week for a crew member to have a family conference?

Family conferences are scheduled once per week using the VHF FM voice system and two-way television, if the television system is available. The duration of these conferences is typically 20–30 minutes. Additional time to communicate with family and friends is available using amateur radio equipment on-board. Amateur radio communications sessions were done at crew discretion.

6. How many crew hours per day are allocated to maintenance, repair, and/or science? How does the actual experience compare to the allocation?

Timeline content is very mission dependent. Scheduled work activity is approximately 11 hours per crew workday. During Phase 1 of the ISS program, the actual crew work activity often exceeded the scheduled amount of time depending on the type of work being performed and the presence of systems malfunctions on board the station.

REFERENCE

NASA (National Aeronautics and Space Administration). 1998. Phase 1 Lessons Learned. August 26, 1998. Houston, Texas: NASA Johnson Space Center.

Acronyms and Abbreviations

AERCam	autonomous extravehicular activity robotic camera
ATV	autonomous transfer vehicle
CAV	Cost Assessment and Validation (Task Force)
CCTV	crew and cargo transfer vehicle
CRV	crew return vehicle
EELV	enhanced expendable launch vehicle
ELV	expendable launch vehicle
EMU	extravehicular mobility unit
ERA	European robotics arm
EVA	extravehicular activity
FDIR	failure detection, isolation, and recovery
FMEA	failure modes and effects analysis
FY	fiscal year
HST	Hubble Space Telescope
HTV	H-II transfer vehicle
HUT	hard upper torso
ISS	International Space station
ISSA	International Space Station Alpha
IVA	intravehicular activity
JEM	Japanese experiment module
LSS	life support system
NASA	National Aeronautics and Space Administration
ORU	orbital replacement unit
P^3I	Preplanned Product Improvement (program)
PI	principal investigator
PLSS	primary life support system
RLV	reusable launch vehicle
SAFER	simplified aid for EVA rescue
SPDM	special purpose dexterous manipulator
SR&M	safety, reliability, and maintainability
SSA	space suit assembly
SSRMS	space station remote manipulator system
TDRSS	tracking and data relay satellite system
fps	feet per second
KBS	kilobits per second
Kg	kilogram
Km	kilometer
kPa	kilopascals
lb	pound
m/s	meters per second
Mbps	megabits per second
nmi	nautical mile
psia	pounds per square inch (absolute)
Δv	delta velocity (change in velocity)

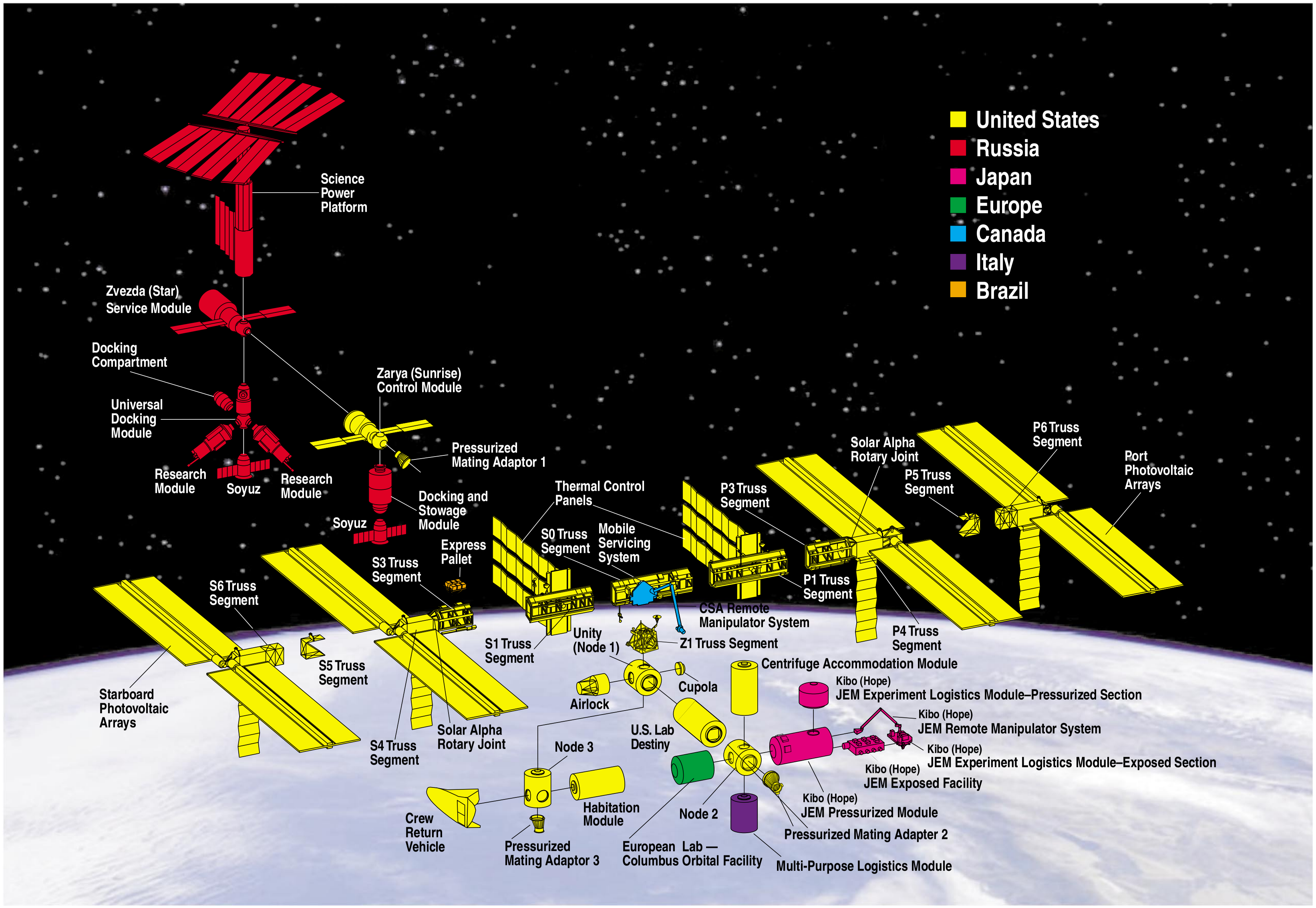

FIGURE ES-1 International space station assembly. Source: NASA, 1999.

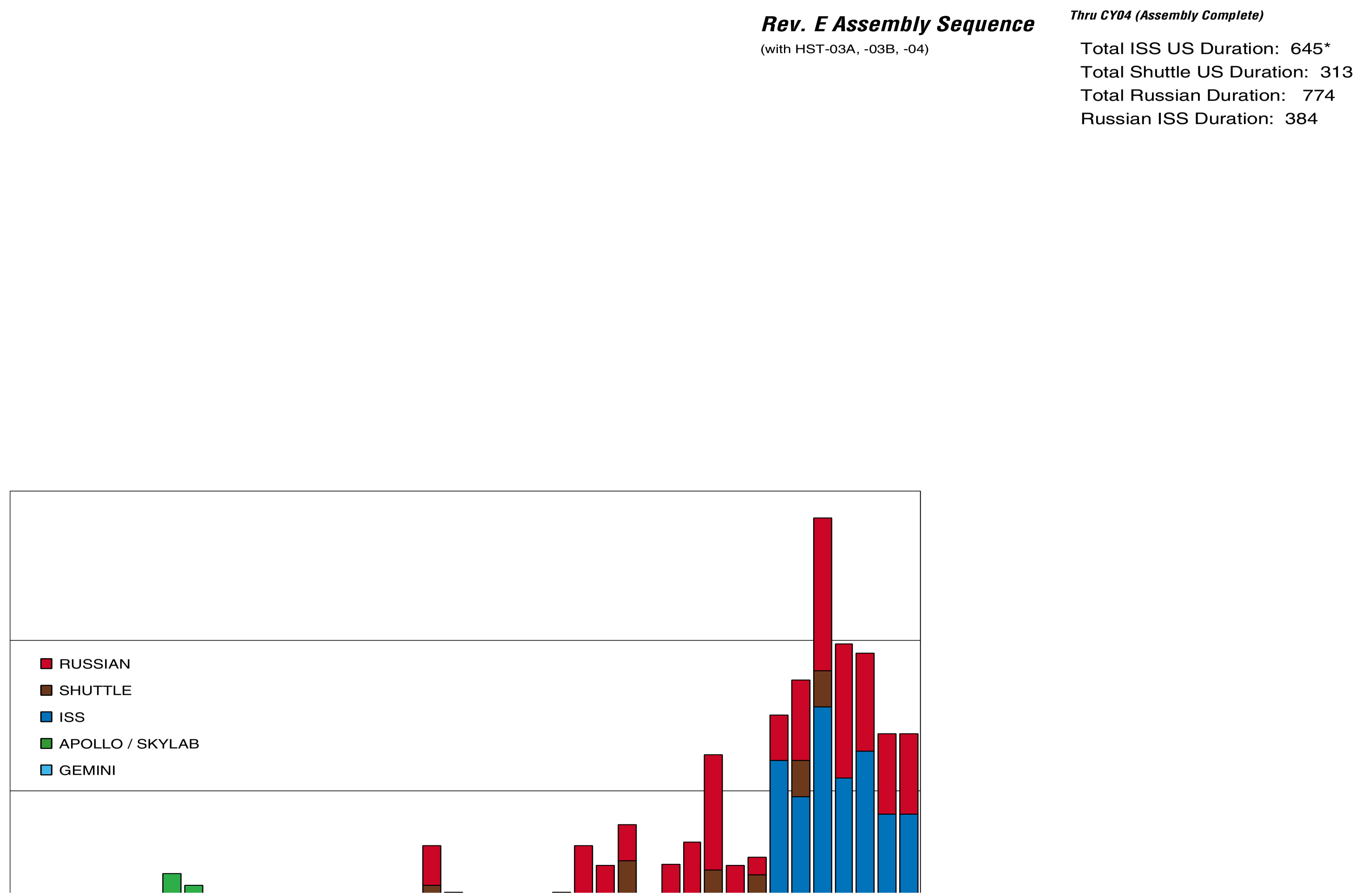

FIGURE 4-1 Total extravehicular activity. Source: NASA, 1999.